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Coal Fired Power Plant Trace Element Study. Volume I. A Three Station Comparison

Radian Corp.

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COAL FIRED POWER PLANT TRACE ELEMENT STUDY

A

THREE STATION COMPARISON

ENVIRONMENTAL PROTECTION AGENCY
ROCKY MOUNTAIN-PRAIRIE REGION
REGION VIII

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COAL FIRED POWER PLANT
TRACE ELEMENT STUDY

VOLUME I
A THREE STATION COMPARISON

SEPTEMBER 1975

PREPARED FOR

ENVIRONMENTAL PROTECTION AGENCY
REGION VIII
DENVER, COLORADO

BY

RADIAN CORPORATION
AUSTIN, TEXAS

TS-1a

FOREWORD

The four volumes comprising this document describe a coal-fired power plant trace element study prepared under EPA Contract 68-01-2663.

This work was conducted under the direction of Mr. Terry L. Thoem, Project Officer, Environmental Protection Agency, Region VIII, Denver, Colorado. The Radian program staff included Dr. F. G. Mesich as Program Manager and Dr. K. Schwitzgebel as Technical Project Director. Principle contributors were Mr. R. A. Magee, Dr. F. B. Meserole and Mr. R. G. Oldham.

Acknowledgement is given to the station personnel from each utility company whose full cooperation greatly facilitated the field work. Mr. R. M. Mann, Mrs. G. E. Wilkin and Mrs. C. M. Thompson contributed significantly to the program during sampling and analysis.

ABSTRACT

This report summarizes the results of a program to characterize the trace element emissions from three coal-fired electric generating stations. A material balance approach was used for a quantitative examination of twenty-seven elements. An additional twenty-six elements were surveyed semiquantitatively.

The trace elements can be broadly classed into three general groups; (1) those uniformly distributed in the coal ash, (2) those preferentially emitted with the fly ash, and (3) those emitted as vapors in the flue gas.

The selection of stations using different coals with different boiler and particulate collection configurations provided a comparison of trace element emissions as a function of plant design and operating parameters.

The overall report is presented in four volumes. Volume I compares the three stations. Volumes II, III and IV give detailed results and descriptions of the methodology used for the individual stations.

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TABLE OF CONVERSION UNITS

To Convert From	To	Multiply By
BTU	Calories, kg	0.25198
BTU/pound	Calories, kg/kilogram	0.55552
Cubic feet	Cubic meters	0.028317
Cubic yards	Cubic meters	0.76455
Feet	Meters	0.30480
Feet/second	Meters/second	0.30480
Gallons (U.S. liq.)	Cubic meters	0.0037854
Gallons (U.S. liq.)	Liters	3.7854
Gallons/minute	Cubic meters/minute	0.0037854
Grains/cubic foot	Grams/cubic meter	2.2884
Inches	Centimeters	2.5400
Inches of H_2O ($4^{\circ}C$)	Millimeters Hg ($0^{\circ}C$)	1.8683
Pounds	Kilograms	0.45359
Pounds/BTU	Kilogram/calorie, kg	1.8001
Pounds/hour	Kilograms/hour	0.45359
Pounds/standard cubic foot ($60^{\circ}F$, 29.92 inches Hg)	Kilograms/standard cubic meter ($0^{\circ}C$, 760 mm Hg)	15.155
Tons	Metric tons	0.90719
Yards	Meters	0.9144

1.0 INTRODUCTION

As natural gas and petroleum resources become less available and more costly, coal will receive increasing emphasis as a primary domestic energy source. The use of the extensive Northern Great Plains area coal deposits may provide a significant portion of the United States' energy requirements for the foreseeable future. The most common utilization of coal will continue to be the conversion to electrical energy by coal-fired generating stations.

The combustion process produces a wide variety of emissions and effluents ranging from sulfur and nitrogen oxides and particulates in the flue gas to solid and liquid wastes. In addition to carbonaceous material, coal contains inorganic matter in the form of mineral inclusions in the coal which becomes part of the emissions and effluents from the generating station. The distribution of this material among the effluent streams of a generating station is dictated by the coal composition, station boiler configuration and the flue gas particulate control devices utilized. As a part of this inorganic material, the minor and trace elements in the coal are distributed among the ash streams dependent on the properties of each element.

This report describes in four volumes the detailed characterization of 27 trace and minor elements in the material flows around three coal-fired steam generating stations. Volume I gives brief descriptions of the stations, the general sampling and analytical approach, and the mass flow results for the elements. The discussion in this volume concentrates on comparisons among the three stations and consistencies of element behavior. The remaining three volumes give detailed descriptions for each of the individual stations. The three

stations include examples of two boiler designs, tangentially fired and cyclonic, and three flue gas particulate control techniques: venturi scrubber, electrostatic precipitator, and mechanical cyclones.

2.0 SAMPLING

The sampling scheme for each of the stations was designed to collect representative samples and mass flow rate data for each incoming and exiting material stream. The three stations operated at relatively constant boiler load during the sampling periods, thus approximating steady state conditions. Therefore, long-term averaging of samples and flow rates were not required to obtain representative data. The following sections describe briefly the three plants, the sampling and sample handling techniques and the flow rate determinations. Detailed descriptions for each station are given in the individual volumes which constitute the remainder of this report.

2.1 Plant Descriptions

Station I consists of four individual units with a total generating capacity of 750 MW fired with Wyoming sub-bituminous coal. Unit No. 4 was sampled for this program. This unit is a tangentially-fired, balanced draft 330 MW boiler with three venturi scrubbers for particulate emission control. A schematic of Unit No. 4 at Station I with approximate sample point locations is presented in Figure 2-1 and the incoming and exiting streams are illustrated in Figure 2-2.

Station II has a 350 MW boiler tangentially-fired with Wyoming sub-bituminous coal. A hot-side electrostatic precipitator provides fly ash control. The physical arrangement of Station II with sample point locations is presented schematically in Figure 2-3. Figure 2-4 illustrates the incoming and exiting material streams.

FIGURE 2-1 SCHEMATIC OF STATION I

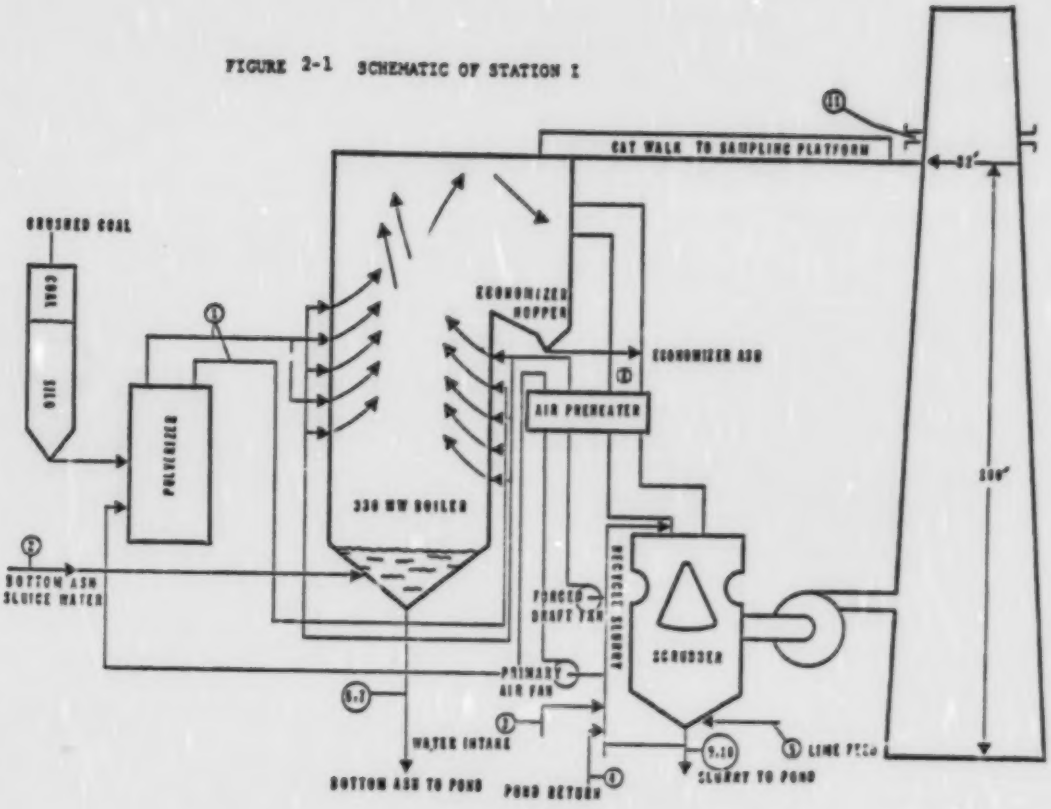


FIGURE 2-2
IN AND OUTGOING STREAMS AT THE
BOILER NO. 4 SCRUBBER SYSTEM AT STATION I

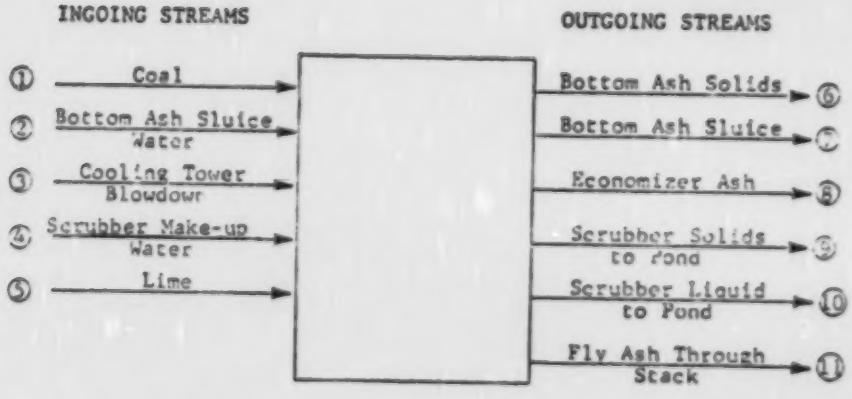


FIGURE 2-3 SCHEMATIC OF STATION II

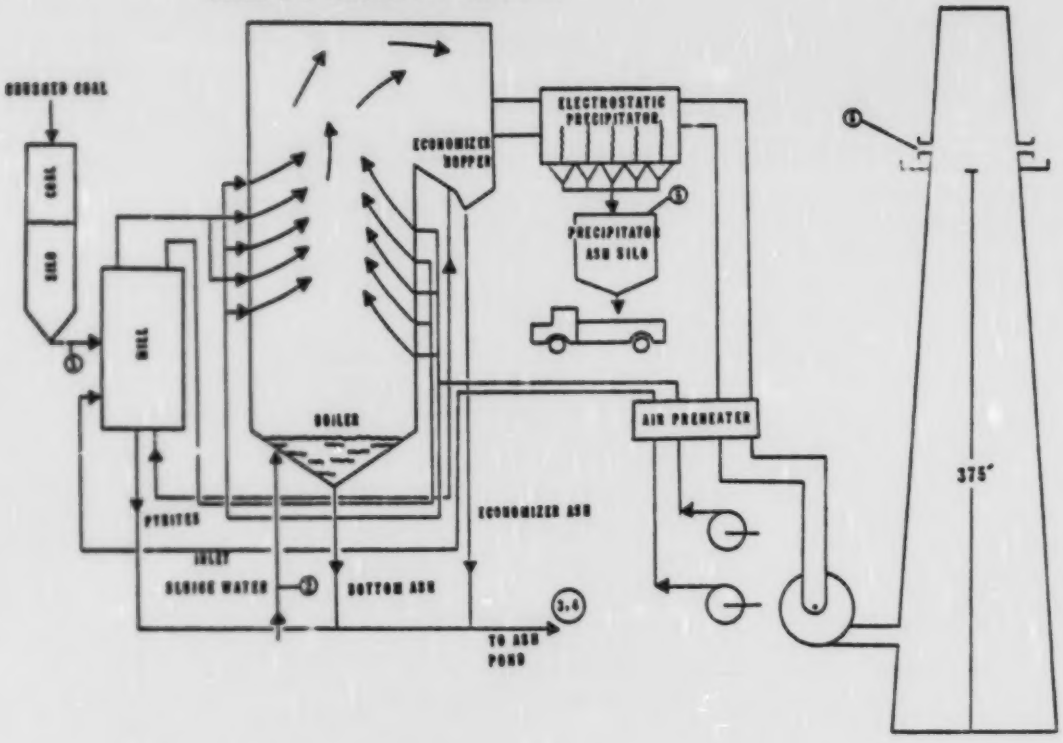
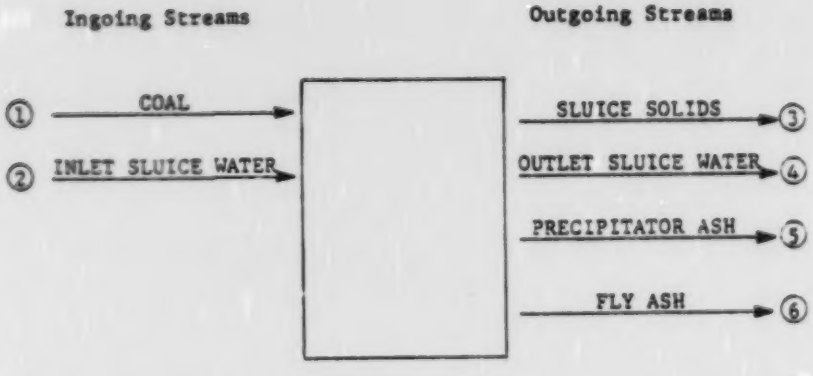


FIGURE 2-4

IN AND OUTGOING STREAMS
AT STATION II



A North Dakota lignite is fired in a 250 MW cyclonic boiler with mechanical cycl ne particulate collectors at Station III. Figure 2-5 is a schematic of the plant with the sample point locations indicated. The incoming and exiting streams are listed in Figure 2-6.

2.2 Sampling Techniques

All incoming and exiting streams at each plant were sampled concurrently over a two-day period. Fly ash in the exiting flue gas was collected using wet electrostatic precipitator (WEP) sampling devices. The collection efficiency of this device was found to be 99+% when compared to the recommended EPA filter technique. The capability of long-term sampling and excellent sample recovery coupled with its high collection efficiency make this sampling technique especially suitable for trace element determination in the flue gas.

Solid, liquid, and slurry streams were sampled periodically during the sampling period. The individual solid samples were combined and representative portions obtained by random splitting either by quartering or with riffle buckets. Composite samples of the solids and liquids in slurry streams were obtained by combining the individual samples and separation of solids and liquids by filtration. Composite samples of liquid streams were also obtained by combination of the individual samples. Liquid samples were acidified to prevent adsorption of trace constituents on the walls of the polypropylene containers.

2.3 Flow Rate Determinations

The mass flow rate of each stream was determined either by direct measurement, from plant operating data or from material balance calculations for total mass flow or mass flow of a major

Figure 2-5 SCHEMATIC OF STATION III

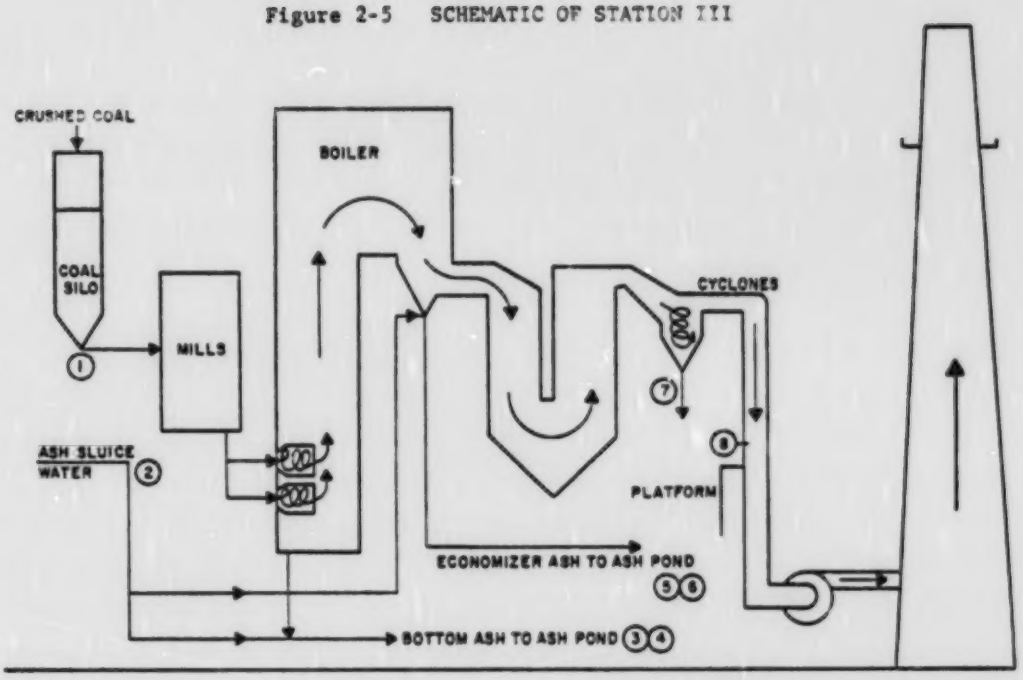
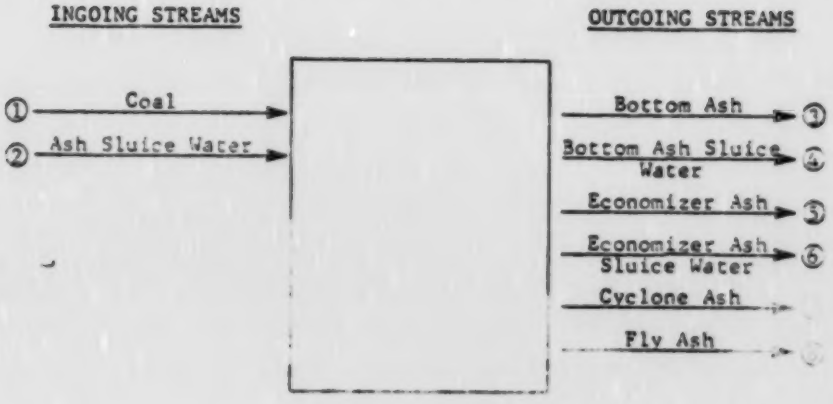


FIGURE 2-6

In and Outgoing Streams
at Station III



constituent. The flow rates for the streams at each station, the estimated error in the flow determination, and a brief description of the method of determination are presented in Tables 2-1, 2-2, and 2-3.

TABLE 2-1
FLOW RATES FOR STREAMS AROUND STATION I

Stream	Flow Rate	Error Limit	Method Used For Flow Determination
Coal	2.83×10^5 lb/hr.	±10%	Control room print-out and heat balance
Bottom Ash Sluice Water Inlet	1.29×10^6 lb/hr.	±15%	Pump power consumption and pump curves
Cooling Tower Blowdown	4.39×10^5 lb/hr.	±15%	Pump heads and pump curves
Scrubber Make-up Water	4.00×10^6 lb/hr.	±10%	Flowmeters
Lime	4.78×10^3 lb/hr.	±15%	Calculated from calcium material balance
Bottom Ash	1.15×10^4 lb/hr.	±40%	Calculated from total ash balance
Bottom Ash Sluice Water Outlet	1.29×10^6 lb/hr.	±15%	Rate was set equal to inlet sluice water
Scrubber Solids	5.00×10^4 lb/hr.	±20%	Calculated from slurry solids content and flow rate of scrubber liquid
Scrubber Liquid	4.18×10^6 lb/hr.	±10%	Calculated from total water balance around scrubbers
Economizer Ash	26.3 lb/hr.	±10%	Measured directly by volume and known density
Flue Gas	5.01×10^7 scfh	±10%	Measured by stack traverses
Fly Ash	1.65×10^2 lb/hr.	±10%	Determined from cumulative grain loadings

TABLE 2-2

FLOW RATES FOR STREAMS AROUND STATION II

Stream	Flow Rate	Error Limit	Method Used for Flow Determination
Coal	2.75×10^5 lb/hr	±10%	Metered at coal feeders
Inlet Sluice Water	5.02×10^5 lb/hr	±15%	Pump heads and pump curves
Sluice Solids	4.4×10^3 lb/hr	±25%	Plant personnel estimate of ash distribution and total ash from coal
Sluice Liquid	5.02×10^5 lb/hr	±15%	Rate set equal to inlet sluice water
Precipitator Ash	1.53×10^4 lb/hr.	±10%	Plant personnel estimate of ash distribution and total ash from coal
Flue Gas	5.46×10^7 scfh	±10%	Measured by stack traverses
Fly Ash	1.40×10^2 lb/hr	±10%	Determined from cumulative grain loadings

TABLE 2-3
FLOW RATES FOR STREAMS AROUND STATION III

Stream	Flow Rate	Error Limit	Method Used For Flow Determination
Coal	2.34×10^5 lb/hr.	±10%	Revolutions of coal feeders were measured
Bottom ash and economizer ash sluice water inlet	2.65×10^5 lb/hr.	±15%	Rates were set equal to sluice water outlet rates
Bottom ash	1.68×10^4 lb/hr.	±15%	Difference of ash rate in incoming coal and discharge rates of economizer ash, cyclone ash and fly ash
Bottom ash sluice water outlet	1.78×10^5 lb/hr.	±15%	Directly measured and corrected for solids content
Economizer ash	154 lb/hr.	±20%	Calculated from economizer ash sluice rate
Economizer ash sluice water outlet	8.71×10^4 lb/hr.	±15%	Directly measured and corrected for solids content
Cyclone ash	6.23×10^3 lb/hr.	±10%	Measured by weighing trucks and from differences in silo level
Flue gas	4.11×10^7 scfh	±10%	Measured by duct traverses
Fly ash	3.42×10^3 lb/hr.	±10%	Determined from point grain loadings

3.0 ANALYTICAL STRATEGY

The samples were quantitatively analyzed for 27 trace and minor elements. These analyses were based on five general techniques:

(1) atomic absorption spectroscopy
(2) X-ray fluorescence
(3) ion selective electrodes
(4) fluorometry, and
(5) colorimetry

Four general sample types were encountered at the three plants:

(1) coal
(2) coal ash and sludge
(3) lime
(4) aqueous, including WEP liquor

The analytical schemes for these sample types are illustrated schematically in Figure 3-1 through 3-4. A detailed description of the analytical techniques is contained in the individual plant volumes, Appendix B.

Semiquantitative analyses by spark source mass spectrometry (SSMS) for 53 elements, including the 27 analyzed quantitatively, were performed by Accu-Labs, Inc. Proximate and ultimate analysis of the coal and mineral analysis and viscosity calculations for the coal ash were also performed by Accu-Labs, Inc.

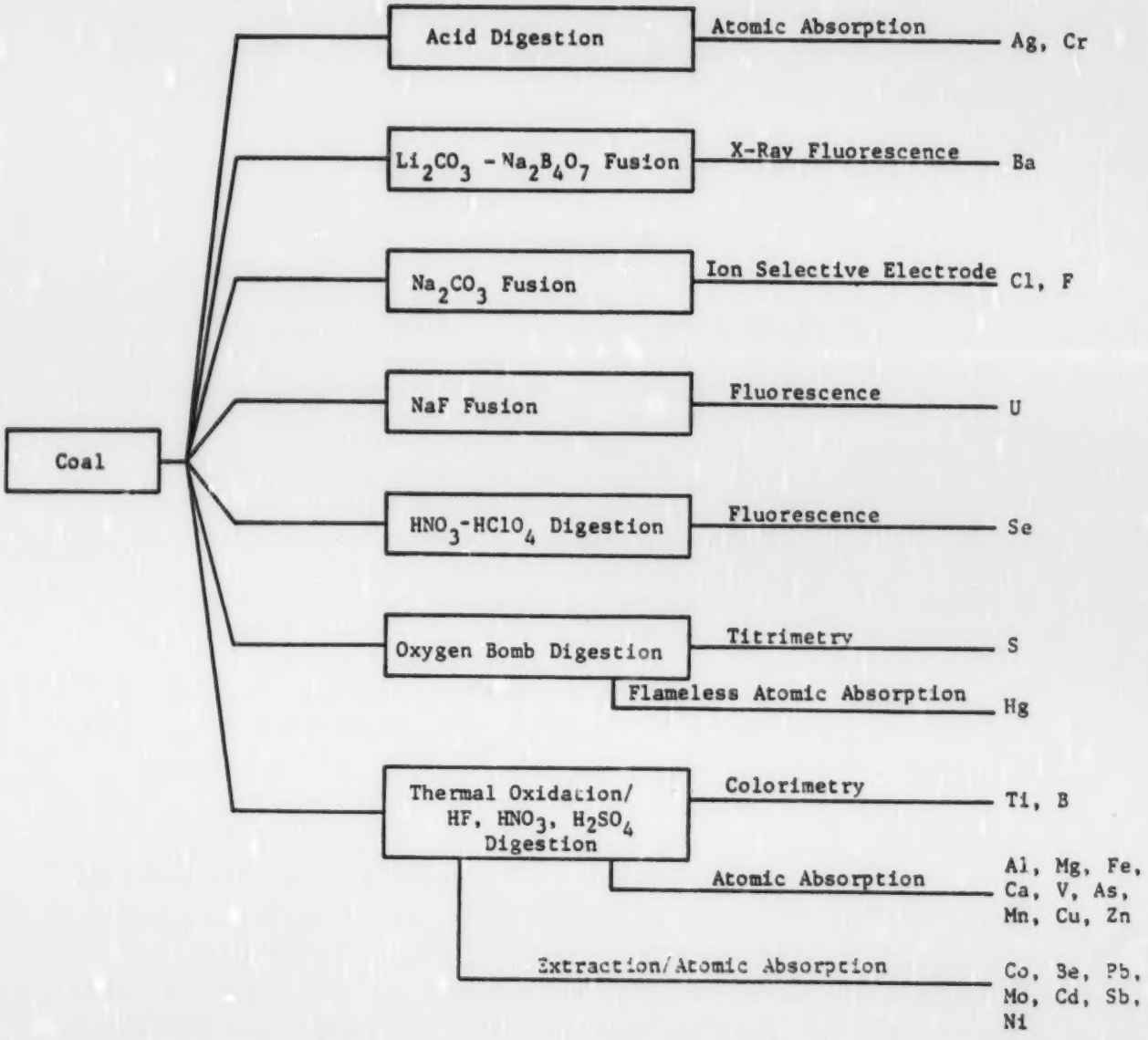


FIGURE 3-1

ANALYTICAL PROCEDURE FOR TRACE ELEMENT ANALYSIS OF COAL

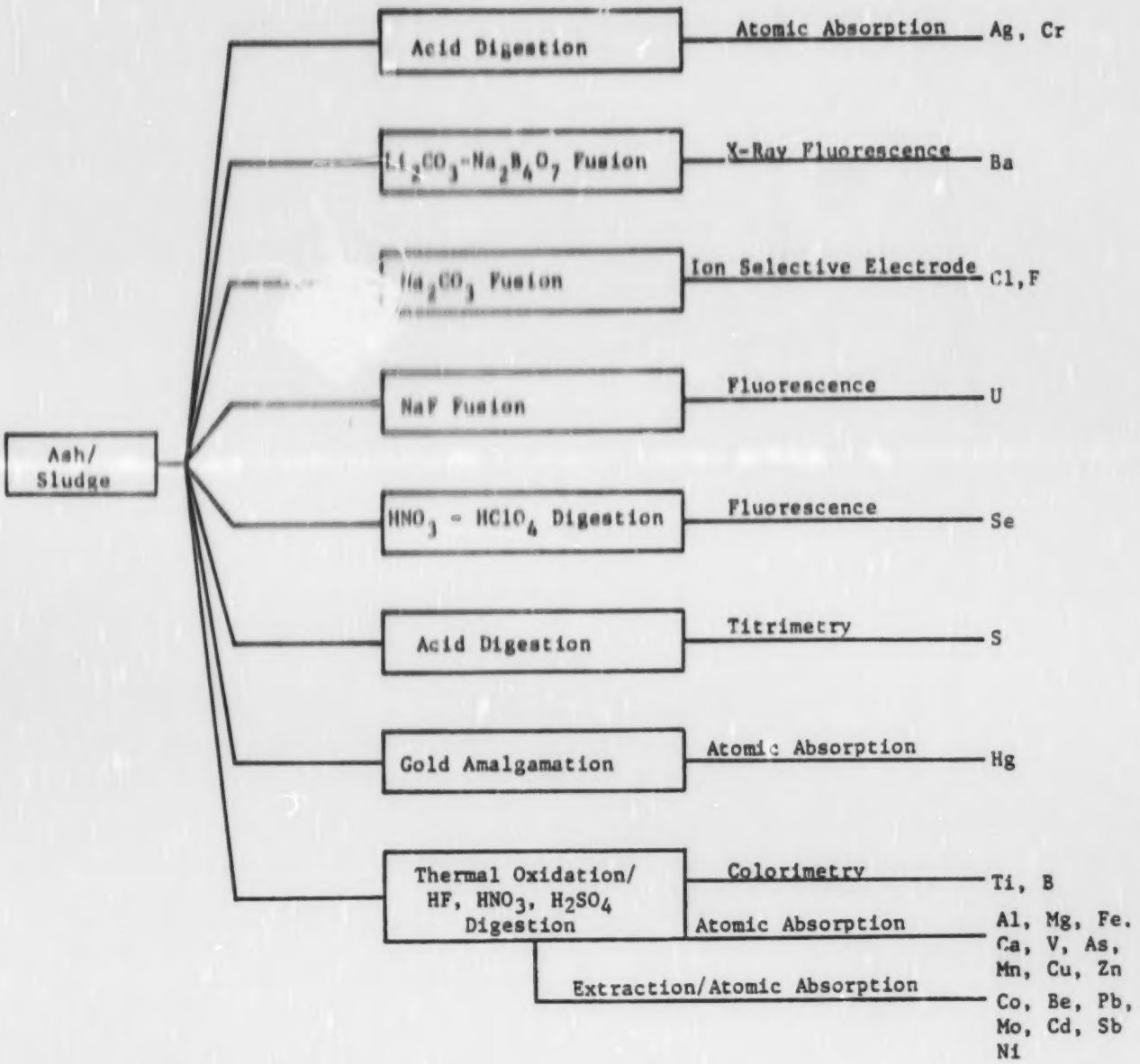


FIGURE 3-2

ANALYTICAL PROCEDURE FOR TRACE ELEMENT ANALYSIS
OF COAL ASH AND SLUDGE

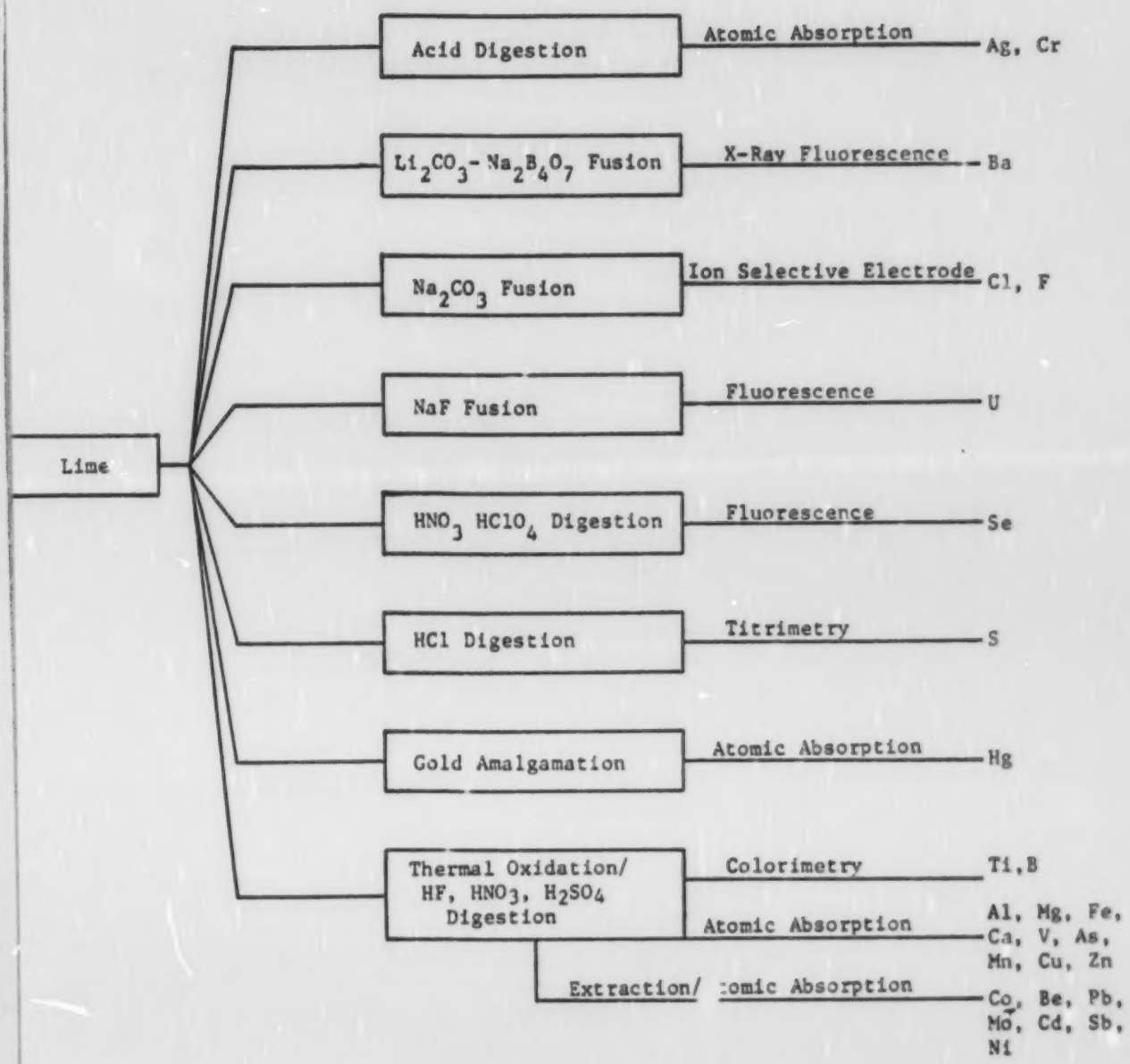


FIGURE 3-3

ANALYTICAL PROCEDURE FOR TRACE ELEMENT ANALYSIS OF LIME

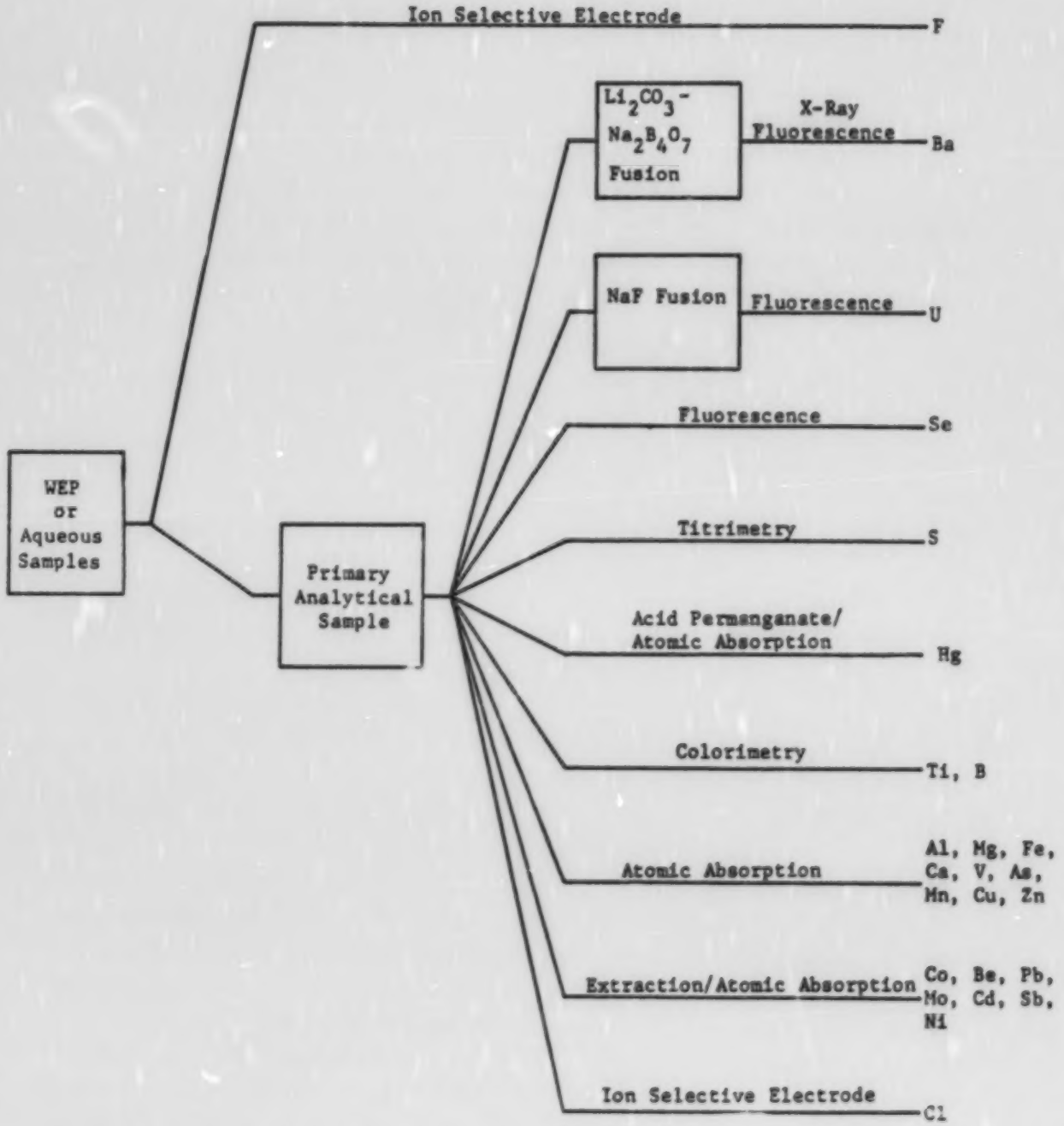


FIGURE 3-4

ANALYTICAL PROCEDURE FOR TRACE ELEMENT ANALYSIS
OF WET ELECTROSTATIC PRECIPITATOR LIQUORS AND AQUEOUS SAMPLES

4.0 RESULTS

From the analytical results and mass flow rate determinations, mass flows for each element in each plant stream were calculated. Material balances were calculated for each element around each plant according to the general expression

$$\sum_{i}^{In} M_i XW_i(j) = \sum_{k}^{Out} M_k XW_k(j) \qquad (4\text{-}1)$$

where,

$\sum_{i}^{In} M_i XW_i(j)$ = the summation of the mass flows of the element j in the incoming streams (lb/hr)

$\sum_{k}^{Out} M_k XW_k(j)$ = the summation of the mass flows of the element j in the exiting streams (lb/hr)

M_i, M_k = the mass flow of the k^{th} or i^{th} stream (lb/hr)

$XW_i(j)$, $XW_k(j)$ = the weight fraction of the element j in the k^{th} or i^{th} stream

The results of these calculations from the quantitative analytical results for the three plants are presented in Tables 4-1, 4-2, and 4-3. The error limits presented for the summations are derived from propagation of the analytical and flow rate errors through the material balance calculations. Tables 4-4, 4-5, and 4-6 list the results of the material balance calculations based on the spark source mass spectrometry (SSMS) results. In general, the results of SSMS survey analyses are no more than order-of-magnitude accuracy due to several important limitations of the technique: (1) It is extremely difficult to provide accurate blank and standard samples to compensate for matrix

effects. (2) Significant losses of some elements are unavoidable during preparation aqueous samples. (3) Physical properties of the prepared samples such as homogeneity and particle size are difficult to reproduce from sample to sample.

TABLE 4-1 TRACE ELEMENT FLOWS* AND MATERIAL BALANCE RESULTS AROUND STATION I (9/14/74)

Element	Coal	Ash Sluice Water	Cooling Tower Blowdown	Make-Up Water	Lime	Σ In	Bottom Ash	Ash Sluice Water	Scrubber Solids	Scrubber Liquid	Economizer Ash	Flue Gas	Σ Out	Σ Out/Σ In
Aluminum	6509	6.5	1.0	20	14	6550 ± 830	1180	3	5400	20	2.6	16.5	6630 ± 1260	1.01
Antimony	.15	.03	.01	.096	.003	.29 ± .03	.0045	.053	.12	.15	.00005	.0017	.33 ± .04	1.14
Arsenic	.23	.0058	.0013	.018	.0003	.26 ± .03	.015	.0053	.26	.0054	.00008	.021	.31 ± .06	1.19
Barium	37	.65	.22	2	.19	40 ± 8	7.7	.65	42	2	.02	.41	53 ± 12	1.33
Beryllium	.23	.0017	.0016	.0052	.0057	.25 ± .03	.029	.0017	16	.0063	.00008	.0012	.20 ± .04	.80
Boron	16	6.1	.12	13	.03	32 ± 3	1.8	3.2	11	12	.0068	.67	28 ± 3	.88
Cadmium	.051	.0070	.0006	.022	.0022	.082 ± .009	.012	.0049	.09	.028	.0002	.0078	.14 ± .02	1.71
Calcium	4980	1019	61	3160	2557	11,800 ± 700	995	1019	5900	3804	3	96	11,800 ± 1300	1.00
Chlorine	12	36	11	112	.60	170 ± 17	2	36	6	117	.005	18	180 ± 18	1.06
Chromium	5.9	.095	< .025	.30	.057	6.4 ± .8	.77	.15	5.9	.59	.0030	.76	8 ± 1	1.25
Cobalt	.59	.010	.011	.032	.0067	.66 ± .08	.081	.0065	.41	.046	.0004	.013	.6 ± .1	.91
Copper	9.6	.046	.11	.14	.081	10 ± 2	1.1	.031	7.8	.20	.0028	.058	9 ± 2	.90
Fluorine	40	26	.40	80	2	150 ± 12	1.2	21	41	84	.0032	.85	150 ± 14	1.00
Iron	1132	.6	.5	1	6	1140 ± 130	289	.4	1125	3	.6	9	1430 ± 260	1.25
Lead	1.2	.010	.007	.032	.053	1.3 ± .2	.082	.009	2.5	.096	.0004	.05	2.7 ± .7	2.08
Magnesium	821	88	16	272	22	1200 ± 90	138	88	680	259	.4	9	1170 ± 150	.98
Manganese	48	1.1	.044	3.4	.37	53 ± 6	8.0	1.0	50	3.7	.026	.22	60 ± 10	1.13
Mercury	.037	.0006	.0002	.002	.0003	.040 ± .005	.0002	.0006	.0027	.0029	2×10^{-7}	.022	.029 ± .004	.73
Molybdenum	1.1	.045	.022	.14	.022	1.4 ± .2	.043	.072	.52	.063	.0009	.36	1.1 ± .1	.79
Nickel	2.5	.032	.002	.10	.016	2.7 ± .4	.45	.019	1.9	.063	.001	.099	2.5 ± .5	.93
Selenium	.62	.062	.0016	.19	.0013	.88 ± .07	.008	.040	.44	.50	.00001	.017	1.0 ± .1	1.14
Silver	.013	.0004	.0001	.0012	.00006	.014 ± .002	.0013	.0005	.012	.002	2×10^{-6}	.0007	.016 ± .003	1.14
Sulfur	2038	1013	1185	3140	.14	7380 ± 410	.001	993	720	3615	7×10^{-6}	1185	6510 ± 440	.88
Titanium	311	<.13	<.04	<.4	.42	310 ± 40	52	<.13	200	<.4	.13	.79	250 ± 50	.81
Uranium	.37	.013	.0066	.04	.037	.46 ± .04	.15	.007	.18	.036	.0002	.0057	.38 ± .07	.83
Vanadium	14	.20	.062	.63	.15	15 ± 2	2.6	.25	13	.97	.007	.41	18 ± 3	1.20
Zinc	6.8	.13	.18	.40	.030	8 ± 1	.47	.098	9.5	.37	.0015	.25	11 ± 2	1.38

* All values in lb/hr.

TABLE 4-2 TRACE ELEMENT FLOWS* AND MATERIAL BALANCE RESULTS AROUND STATION II (10/23/74)

Element	Coal	Inlet Sluice Water	Σ In	Precipitator Ash	Sluice Ash	Outlet Sluice Water	Flue Gas	Σ Out	Σ Out/Σ In
Aluminum	1950	<.05	1950 ± 250	1830	480	4.6	17	2330 ± 270	1.19
Antimony	.044	.0012	.045 ± .008	.035	<.0004	.0019	.0016	.040 ± .006	.89
Arsenic	.70	<.00005	.7 ± .1	.73	.0062	<.00005	.0004	.7 ± .1	1.00
Barium	127	<.30	130 ± 28	119	23	<.30	<.14	140 ± 28	1.08
Beryllium	.080	<.0010	.08 ± .01	.086	.018	<.0010	<.0023	.11 ± .013	1.38
Boron	8.5	.09	8.6 ± 1	8.4	1.1	.25	.50	10 ± 1	1.16
Cadmium	<.028	<.0010	<.029	.018	.0037	<.0010	<.0009	<.024	--
Calcium	3000	29	3030 ± 310	2980	660	57	30	3730 ± 350	1.23
Chlorine	2.6	4.3	6.9 ± .8	.72	<.004	7.5	16	25 ± 3	3.62
Chromium	2.5	<.027	2.6 ± .4	1.8	.34	<.027	.32	2.5 ± .3	.96
Cobalt	.41	<.0015	.41 ± .06	.41	.079	<.0015	.0081	.5 ± .06	1.22
Copper	8.5	.0080	8.5 ± 1	7.0	1.0	.011	.068	8 ± 1	.94
Fluorine	18	.23	19 ± 2	17	.084	.35	1.5	19 ± 2	1.00
Iron	580	.080	580 ± 70	450	180	.0050	5.2	640 ± 70	1.10
Lead	.63	.0085	.64 ± .13	.34	.048	.0030	.033	.42 ± .07	.66
Magnesium	413	7.4	420 ± 40	428	91	7.9	4.4	530 ± 50	1.26
Manganese	6.6	.017	6.6 ± .8	6.2	1.4	.0080	.10	7.7 ± .9	1.17
Mercury	.037	.040	.077 ± .009	<.0002	<.00004	<.0002	.0093	.010 ± .002	.13
Molybdenum	.18	<.0001	.18 ± .03	.13	.015	.0075	.017	.17 ± .02	.94
Nickel	.58	<.010	.59 ± .09	.57	.12	<.010	.16	.86 ± .1	1.46
Selenium	.44	.0009	.44 ± .05	.10	.0015	.0019	.068	.17 ± .01	.39
Silver	.013	<.0001	.013 ± .002	.014	.0005	<.0001	.0002	.015 ± .002	1.15
Sulfur	1350	7	1358 ± 140	120	4.0	54	1300	1480 ± 180	1.10
Titanium	160	<.05	160 ± 20	146	40	<.05	1.2	190 ± 20	1.19
Uranium	.24	.0042	.25 ± .03	.089	.022	.0022	.0017	.11 ± .01	.44
Vanadium	5.5	.029	5.5 ± .8	4.5	.84	.036	.14	5.5 ± .7	1.00
Zinc	1.1	.20	1.3 ± .2	1.2	.69	.0042	.046	1.9 ± .3	1.46

*All values in lb/hr.

TABLE 4-3

TRACE ELEMENT FLOWS* AND MATERIAL BALANCE RESULTS AROUND STATION III (8/29/74)

Element	Coal	Ash Sluice Water	Σ In	Bottom Ash	Bottom Ash Sluice Water	Economizer Ash	Economizer Ash Sluice Water	Cyclone Ash	Flue Gas South Duct	Flue Gas North Duct	Σ Out	Σ Out/Σ In
Aluminum	1740	0.11	1740 ± 229	1480	.39	13.	.05	463	164	82	2200 ± 260	1.26
Antimony	.094	.0046	.10 ± .02	.013	.0061	.00008	.0018	.0049	.040	.025	.09 ± .01	.90
Arsenic	1.9	.0016	1.9 ± .3	.33	.0015	.019	.0001	1.2	.15	.25	1.9 ± .2	1.00
Barium	102	.13	103 ± 23	96	< .089	1.3	< .044	48.	< 1.3	< 1.0	147 ± 26	1.43
Beryllium	.14	.0004	.14 ± .02	.089	.0003	.0014	.0003	.052	.006	.004	.15 ± .02	1.07
Boron	36	.07	36 ± 5	8.7	.045	.11	.21	10.	16.	6.4	42 ± 3	1.17
Cadmium	.046	.00007	.046 ± .007	.015	.0002	.0003	.0001	.018	.012	.011	.056 ± .005	1.22
Calcium	3220	9	3230 ± 330	2180	8.	18.	4.	816.	397.	204.	3630 ± 340	1.12
Chlorine	13	3.2	16 ± 2	1.5	2.8	.02	1.5	.84	6.4	8.0	21 ± 2	1.31
Chromium	3.1	<.014	3.1 ± .4	1.6	<.0094	.019	<.0046	.54	.78	.68	3.6 ± .4	1.16
Cobalt	.18	.00007	.18 ± .02	.17	.0007	.0018	.0003	.081	.062	.039	.35 ± .03	1.94
Copper	2.5	.022	2.5 ± .4	.84	.002	.014	.0007	.90	.42	.29	2.5 ± .2	1.00
Fluorine	13.	.05	13 ± 2	<.17	.044	.01	.02	4.2	6.4	6.1	17 ± 2	1.31
Iron	1770	.11	1770 ± 210	1100	.4	10.	.12	358	2.08	103	1750 ± 180	1.01
Lead	.20	.0040	.21 ± .04	<.013	.0043	.0013	.0022	.051	.062	.062	.20 ± .02	.95
Magnesium	870	7	880 ± 90	623	4.6	5.8	2.1	226	100	49	1010 ± 100	1.15
Manganese	18	.022	18. ± 2	12	.0098	.14	.0084	4.7	1.6	.8	19 ± 2	1.06
Mercury	.017	<.0001	.017 ± .002	<.0002	<.00008	.00001	<.00004	.0011	.018	.016	.036 ± .004	2.12
Molybdenum	.46	.0087	.47 ± .08	.30	.0028	.0068	.0010	.38	.46	.70	1.9 ± .2	4.04
Nickel	1.3	.0016	1.3 ± .2	.39	.0002	.0055	.0006	.24	.52	.56	1.7 ± .2	1.31
Selenium	.31	.0003	.31 ± .03	.0042	.0002	.00002	.0001	.059	.070	.049	.18 ± .01	.58
Silver	.0079	<.00006	.008 ± .001	.0018	<.00004	.0004	<.00002	.0047	<.0007	<.0006	.0078 ± .0007	.98
Sulfur	3380	18	3400 ± 340	1.6	13.	.20	6.7	54.	1560	1390	3020 ± 300	.89
Titanium	82.	<.027	82 ± 10	59	<.018	.59	<.0067	19.	3.4	3.3	85 ± 10	1.04
Uranium	.36	.0006	.36 ± .04	.054	.0006	.0017	.0004	.075	.034	.016	.18 ± .02	.50
Vanadium	3.5	<.0313	3.5 ± .5	2.4	<.0009	.017	<.0004	.54	.57	.41	3.9 ± .4	1.11
Zinc	1.8	.0034	1.8 ± .3	.30	.0023	.022	.0024	.75	.78	.47	2.3 ± .3	1.28

*All flow rates in lb/hr.

TABLE 4-4 TRACE ELEMENT FLOWS* AND MATERIAL BALANCE RESULTS AROUND STATION I FROM SPARK SOURCE MASS SPECTROMETRY ANALYSES

Element	Coal	Bottom Ash Sluice Water	Cooling Tower Blowdown	Make-up Water	Lime	Σ In	Bottom Ash	Bottom Ash Sluice Water	Scrubber Solids	Scrubber Liquid	Economizer Ash	Flue Gas	Σ Out
Aluminum	~2434	2.7	.19	8.4	.27	~2400	>115	17	>500	17	>.26	3.5	>650
Antimony	.12	.014	< .0004	.044	< .0002	.18	.006	.027	.041	.067	.00002	.003	.14
Arsenic	.37	< .006	< .0004	<.02	< .003	.40	.062	< .004	.85	.008	.0002	.005	.93
Barium	37	19	.029	.60	.033	38	3.7	.44	5.5	.92	.003	.079	11
Beryllium	.54	< .001	< .0004	< .004	.001	.54	.13	< .001	.38	< .004	.0001	< .0008	.51
Bismuth	< .20	< .001	< .0004	< .004	< .0004	< .20	.002	< .001	.023	< .004	.00001	.0008	.032
Boron	31	< .13	.088	< .40	.007	32	9.2	< .13	27	< .42	.013	< .083	36
Bromine	.48	.034	< .0004	.10	.001	.62	.017	.071	.049	.075	.00004	< .0008	.21
Cadmium	.18	.062	.057	.19	.0008	.49	.008	.19	.045	.20	.00006	.091	.54
Calcium	>2830	955	48	2960	>48	>6800	>115	929	>500	3511	>.26	34	>5100
Cerium	16	.008	< .0004	.024	.049	16	2.3	.004	5	.017	.002	.013	7.3
Cesium	.19	.003	.002	.008	.00004	.20	.049	.006	.14	.004	.00005	.017	.22
Chlorine	28	.023	.001	.072	.062	28	.30	.36	.85	.39	.0002	.005	1.9
Chromium	8.2	.005	.0008	.016	.003	8.2	1.3	.003	9	.017	.003	.42	11
Cobalt	1.7	.030	.018	.092	.002	1.8	.30	.013	.85	.059	.0004	.025	1.2
Copper	7.1	.067	.057	.21	.006	7.4	1.4	.18	17	.75	.002	.055	19
Dysprosium	.45	< .001	< .0004	< .004	.001	.46	.048	< .001	.14	< .004	.00008	< .0008	.19
Erbium	.14	< .001	< .0004	< .004	.0003	.15	.006	< .001	.024	< .004	.00001	< .0008	< .036
Europium	.23	< .001	< .0004	< .004	.0003	.24	.012	< .001	.035	< .004	.00003	< .0008	.052
Fluorine	93	2.8	--	8.8	2.1	110	1.0	--	15	3.4	.003	.003	19
Gadolinium	.037	< .001	.001	< .004	.0003	< .044	.008	< .001	.055	< .004	.00001	.002	.070
Gallium	1.0	.018	.001	.056	.003	1.1	.31	.008	2.4	.19	.0003	.056	3.0
Germanium	.16	.043	.0004	.13	.0001	.34	.032	.089	.20	.20	.00005	.006	.53
Gold	< .028	< .001	< .0004	< .004	< .0004	< .034	< .001	< .001	< .005	< .004	$< 2 \times 10^{-6}$	< .0008	< .012
Hafnium	.088	< .001	< .0004	< .004	.003	.096	.066	< .001	.090	< .004	.00006	< .0008	.16
Holmium	.042	< .001	< .0004	< .004	.00009	< .048	.004	< .001	.01	< .004	8×10^{-6}	< .0008	< .020

*All flows in lb/hr.

TABLE 4-4 TRACE ELEMENT FLOWS* AND MATERIAL BALANCE RESULTS AROUND STATION I FROM SPARK SOURCE MASS SPECTROMETRY ANALYSES (Cont'd)

Element	Coal	Bottom Ash Sluice Water	Cooling Tower Blowdown	Make-up Water	Lime	Σ In	Bottom Ash	Bottom Ash Sluice Water	Scrubber Solids	Scrubber Liquid	Economizer Ash	Flue Gas	Σ Out
Iodine	.34	< .001	< .0004	< .004	.0008	.35	.007	.005	.01	.004	4×10^{-6}	< .0008	.027
Iridium	< .028	< .001	< .0004	< .004	< .0004	< .034	< .001	< .001	< .005	< .004	$< 2 \times 10^{-6}$	< .0008	< .012
Iron	>1415	.59	.48	1.8	~27	>1400	>115	1.5	>500	3.8	>.26	6.7	>630
Lanthanum	2.5	.004	< .0004	.012	.004	2.6	.36	.013	1.0	.013	.0005	.012	1.4
Lead	.82	.005	.002	.016	< .0004	.84	.092	.017	1.4	.013	.0002	.015	1.5
Lithium	19	.037	.0004	.62	.036	19	9.9	.17	.10	.18	.011	.007	10
Lutetium	.023	< .001	< 0004	< .004	.0001	< .029	.002	< .001	.005	< .004	3×10^{-6}	< .0008	< .013
Magnesium	>2800	90	15	280	~24	>3200	>115	89	>500	272	>.26	7.3	>980
Manganese	23	.67	.016	2.1	.81	26	~38	.52	~110	4.2	~.087	.17	~153
Mercury	.034	--	--	--	< .0004	.034	< .001	--	< .005	--	7×10^{-7}	--	< .006
Molybdenum	4.0	.085	.005	.26	.042	4.4	.40	.18	1.2	.42	.0004	.057	2.2
Neodymium	21	.006	< .0004	.02	.006	21	1.5	.014	4.2	.013	.002	.016	5.7
Nickel	3.7	.59	.034	1.8	.007	6.2	.32	.099	.95	2.9	.0022	.39	4.6
Niobium	1.5	< .001	< .0004	< .004	.002	1.5	.21	< .001	1.2	< .004	.0004	.013	1.4
Osmium	< .028	< .001	< .0004	< .004	< .0004	< .034	< .001	< .001	< .005	< .004	$< 2 \times 10^{-6}$	< .0008	< .012
Palladium	< .028	< .001	< .0004	< .004	< .0004	< .034	< .001	< .001	< 005	< .004	$< 2 \times 10^{-6}$	< .0008	< .012
Phosphorus	181	.083	~.18	.26	.48	182	~21	.14	85	.41	.055	3.8	~110
Platinum	< .028	< .001	< .0004	< .004	< .0004	< .034	< .001	< .001	< .005	< .004	$< 2 \times 10^{-6}$	< .0008	< .012
Potassium	~736	14	3.6	44	.24	~800	~28	15	>250	50	>.13	2	>350
Praseodymium	2.0	.001	< .0004	.004	.001	2.0	.13	.001	.38	< .004	.0001	.002	.51
Rhenium	< .028	< .001	< .0004	< .004	< .0004	< .034	< .001	< .001	< .005	< .004	$< 2 \times 10^{-6}$	< .0008	< .012
Rhodium	< .028	< .001	< .0004	< .004	< .0004	< .034	< .001	< .001	< .005	< .004	$< 2 \times 10^{-6}$	< .0008	< .012
Rubidium	2.5	.58	.018	1.8	.0005	4.9	.26	.11	1.6	.12	.0002	.050	2.2
Ruthenium	< .028	< .001	< .0004	< .004	< .0004	< .034	< .001	< .001	< .005	< .004	$< 2 \times 10^{-6}$	< .0008	< .012

*All flows in lb/hr.

TABLE 4-4 TRACE ELEMENT FLOWS* AND MATERIAL BALANCE RESULTS AROUND STATION I FROM SPARK SOURCE MASS SPECTROMETRY ANALYSES (Cont'd)

Element	Coal	Bottom Ash Sluice Water	Cooling Tower Blowdown	Make-up Water	Lime	Σ In	Bottom Ash	Bottom Ash Sluice Water	Scrubber Solids	Scrubber Liquid	Economizer Ash	Flue Gas	Σ Out
Samarium	.092	< .001	<.0004	< .004	.0002	.099	.022	< .001	.065	< .004	.00002	< .0008	.093
Scandium	3.7	< .001	< .0004	< .004	.008	3.7	.92	< .001	2.7	< .004	.001	< .0008	3.6
Selenium	.45	19	.029	.60	.001	1.3	.010	.25	.29	.54	.00001	.22	1.3
Silver	.063	< .001	.004	< .004	.0001	.077	. .002	.001	.010	.004	5×10^{-6}	< .0008	.017
Sodium	144	98	38	304	1.1	590	∿25	101	>500	334	>.13	14	>974
Strontium	42	8.5	.26	26	1.5	79	11	5.8	43	41	.037	.83	102
Tantalum	< .028	.009	< .0004	.028	.003	< .068	.030	< .001	.04	.004	.00005	.002	.078
Tellurium	.028	< .001	< .0004	< .004	< .0003	< .034	.002	< .001	.005	.004	1×10^{-6}	.0008	.013
Terbium	.025	< .001	< .0004	< .004	.00009	< .031	.005	< .001	.008	< .004	4×10^{-6}	< .0008	< .019
Thallium	< .028	< .001	< .0004	< .004	< .0004	< .034	.002	< .001	.013	< .004	.000008	.006	.026
Thorium	.74	< .001	< .0004	< .004	.003	.74	.15	< .001	.90	< .004	.0003	.0003	1.1
Thulium	.011	< .001	< .0004	< .004	.00009	< .017	.003	< .001	.006	< .004	.00001	< .0008	< .015
Tin	.51	.005	.003	.016	.0008	.53	.023	.005	.16	.050	.00006	.055	.29
Titanium	∿538	.30	.033	.92	.27	∿540	115	< .001	>500	.92	∿.20	1.7	>620
Tungsten	.96	.035	< .0004	.02	.005	.99	.042	.004	.25	.013	.0001	.004	.31
Uranium	.71	.003	< .0004	.008	.006	.72	.26	.003	.36	.013	.0002	.004	.64
Vanadium	21	.25	.003	.76	.006	22	>2.1	.086	14	1.2	.005	.44	18
Ytterbium	.076	< .001	< .0004	< .004	.0007	< .083	.012	< .001	.07	< .004	.00001	< .0008	.088
Yttrium	4.8	.001	< .0004	.004	.010	4.8	.86	.021	2.5	.008	.002	.006	3.4
Zinc	.25	.13	.18	40	.001	.95	.12	.095	3.3	.21	.0006	.22	3.9
Zirconium	8.8	.004	< .0004	.012	.005	8.8	.71	.008	3.8	.017	.001	.012	4.6

*All flows in lb/hr.

TABLE 4-5 TRACE ELEMENT FLOWS* AND MATERIAL BALANCE RESULTS AROUND STATION II FROM SPARK SOURCE MASS SPECTROMETRY ANALYSES

Element	Coal	Make-Up H_2O	Σ In	Precipitator Ash	Sluice Ash	Sluice Ash Filtrate	WEP	Σ Out
Aluminum	>1375	.090	>1400	>162	>46	1.3	9.9	>220
Antimony	.17	.0005	.17	.31	.005	.0005	<.0004	.037
Arsenic	26	.002	26	.24	.042	.002	<.0009	.29
Barium	110	.011	110	~79	>46	.11	.36	>126
Beryllium	.25	<.0005	.25	.018	.012	<.0005	<.0004	.031
Bismuth	<.13	<.0005	<.13	.12	.023	<.0005	<.0004	.14
Boron	9.4	.008	9.4	~23	3.5	.043	.039	~26
Bromine	1.2	.004	1.2	.029	.003	.009	.002	.043
Cadmium	1.0	<.003	1.0	.12	.006	<.003	.003	.14
Calcium	>2750	25	>2800	>162	>46	50	19	>280
Cerium	2.3	<.0005	2.3	4.5	2.4	<.0005	.004	6.9
Cesium	.061	<.0005	.061	.013	.004	<.0005	<.0004	.018
Chlorine	69	--	69	.76	.092	--	--	.85
Chromium	1.7	.027	1.7	.99	.28	.027	.24	1.5
Cobalt	.83	<.0005	.83	.21	.065	<.0005	.003	.28
Copper	4.7	.007	4.7	3.6	.55	.007	.030	4.2
Dysprosium	.74	<.0005	.74	.18	.088	<.0005	<.0004	.27
Erbium	.11	<.0005	.11	.032	.006	<.0005	<.0004	.039
Europium	.072	<.0005	.072	.057	.022	<.0005	<.0004	.080
Fluorine	106	--	106	~34	.97	--	--	~35
Gadolinium	.036	<.0005	.036	.023	.011	<.0005	<.0004	.035
Gallium	.83	<.0005	.83	.26	.040	.011	.018	.33
Germanium	.063	<.0005	.083	.053	.014	.002	.0009	.070
Gold	<.028	<.0005	<.028	<.002	<.0004	<.0005	<.0004	<.003
Hafnium	.28	<.0005	.28	.065	.031	<.0005	<.0004	.097
Holmium	.019	<.0005	.020	.016	.006	<.0005	<.0004	.024
Iodine	.33	.0005	.33	.005	.003	<.0005	<.0004	.009
Iridium	<.028	<.0005	<.028	<.002	<.0004	<.0005	<.0004	<.003
Iron	~633	.085	~630	>162	>46	.27	2.9	>210
Lanthanum	1.2	.002	1.2	.97	.35	.001	.003	1.3
Lead	2.6	.003	2.6	1.2	.069	.003	.006	1.3
Lithium	2.8	.005	2.8	2.7	.55	.001	.0009	3.2
Lutetium	.039	<.0005	.039	.009	.004	<.0005	<.0004	.013
Magnesium	>2750	7.5	>2800	>162	>46	8.0	3.2	>220
Manganese	8.0	.007	8.0	4.1	.23	.007	.050	4.3
Mercury	<.028	<.0005	<.028	<.002	<.0004	<.0005	<.0004	<.003

*All values in lb/hr.

TABLE 4-5 TRACE ELEMENT FLOWS* AND MATERIAL BALANCE RESULTS AROUND STATION II FROM SPARK SOURCE MASS SPECTROMETRY ANALYSES

Element	Coal	Make-Up H_2O	Σ In	Precipitator Ash	Sluice Ash	Sluice Ash Filtrate	WEP	Σ Out
Molybdenum	3.6	.003	3.6	.94	.092	.024	.009	1.1
Neodymium	4.0	<.0005	4.0	3.1	1.2	.0005	.006	4.2
Nickel	.94	.002	.94	1.3	.17	.010	.16	1.6
Niobium	1.1	<.0005	1.1	.39	.24	<.0005	.002	.65
Osmium	<.028	<.0005	<.028	<.002	<.0004	<.0005	<.0004	<.003
Palladium	<.028	<.0005	<.028	<.002	<.0004	<.0005	<.0004	<.003
Phosphorus	~358	.065	~358	>162	~22	.10	2.4	>187
Platinum	<.028	<.0005	<.028	<.002	<.0004	<.0005	<.0004	<.003
Potassium	99	1.4	100	~19	~6.5	2.4	.41	~29
Praseodymium	1.5	<.0005	1.5	.49	.092	<.0005	.0009	.58
Rhenium	<.028	--	<.028	<.002	<.0004	--	<.0004	<.002
Rhodium	<.028	<.0005	<.028	<.002	<.0004	<.0005	<.0004	<.003
Rubidium	.33	.002	.33	.70	.40	.003	.003	1.1
Ruthenium	<.028	<.0005	<.028	<.002	<.0004	<.0005	<.0004	<.003
Samarium	.14	<.0005	.14	.087	.019	<.0005	<.0004	.11
Scandium	2.0	<.0005	2.0	.65	.18	<.0005	.002	.84
Selenium	.74	.001	.74	.14	.006	.005	.022	.18
Silicon	>2750	3.1	>2800	>162	>46	5.5	5.0	>220
Silver	.033	<.0005	.034	.004	.0006	<.0005	<.0004	.006
Sodium	>27.0	14	>2800	>162	>46	22	1.0	>230
Strontium	85	1.0	86	>81	>23	1.8	.90	>107
Sulfur	>2750	~20	>2800	>162	>23	>50	~45	>280
Tantalum	.22	<.0005	.22	.060	.014	<.0005	<.0004	.075
Tellurium	<.028	<.0005	<.028	.009	.0007	<.0005	.001	.011
Terbium	.052	<.0005	.053	.024	.005	<.0005	<.0004	.030
Thallium	<.028	<.0005	<.028	.006	<.0004	<.0005	<.0004	.007
Thorium	.85	<.0005	.85	.22	.083	<.0005	<.0004	.31
Thulium	.030	<.0005	.031	.004	.003	<.0005	<.0004	.008
Tin	.33	.003	.33	.053	.011	.001	.003	.068
Titanium	124	.010	124	>81	>46	.022	.90	>128
Tungsten	.33	<.0005	.33	.096	.03?	<.0005	<.0004	.13
Uranium	.55	.0005	.55	.12	.055	<.0005	<.0004	.17
Vanadium	7.4	.002	7.4	5.8	.97	.030	.054	6.8
Ytterbium	.24	<.0005	.24	.052	.013	<.0005	<.000?	.066
Yttrium	4.7	.0005	4.7	2.9	.74	.001	.045	3.7
Zinc	1.3	.19	1.5	1.2	.27	.040	.036	1.5
Zirconium	4.4	.001	4.4	.71	.78	.001	.018	1.5

*All values in lb/hr.

TABLE 4-6 - TRACE ELEMENT FLOWS* AND MATERIAL BALANCE RESULTS AROUND STATION III FROM SPARK SOURCE MASS SPECTROMETRY ANALYSES

ELEMENT	COAL	ASH SLUICE H_2O	Σ IN	BOTTOM ASH	BOTTOM ASH SLUICE H_2O	ECON ASH	ECON ASH SLUICE H_2O	CYCLONE ASH	FLUE GAS SOUTH DUCT	FLUE GAS NORTH DUCT	Σ OUT
ALUMINUM	410	0.32	410	>168	0.13	>1.5	0.10	>62	62	8	>300
ANTIMONY	0.095	< .0003	0.095	0.042	0.0005	0.0004	<0.00008	0.016	0.052	0.014	0.13
ARSENIC	1.8	0.0013	1.8	0.20	0.0021	0.0088	0.0017	0.75	0.42	0.11	1.5
BARIUM	88	0.082	88	12	0.071	~0.40	0.27	~11	1.0	0.43	~25
BERYLLIUM	0.61	<0.0003	0.61	0.94	<0.0002	0.0017	<0.00006	0.069	0.0026	0.0021	1.0
BISMUTH	<0.19	<0.0003	<0.19	<0.0029	<0.0002	0.0005	<0.00008	0.0093	0.010	0.0021	0.025
BORON	59	<0.027	59	~17	<0.018	~0.34	<0.0087	~16	--	4.1	~37
BROMINE	0.72	0.0066	0.72	0.052	0.012	0.0035	0.0010	0.034	0.023	0.0041	0.13
CADMIUM	0.56	0.0077	0.57	0.022	0.066	0.0004	0.0025	0.0081	1.3	0.19	1.6
CALCIUM	>2560	8.7	>2570	>168	7.3	>1.5	4.1	>62	234	140	>620
CERIUM	3.1	0.0013	3.1	0.67	0.0004	0.011	0.00008	0.44	0.055	0.035	1.2
CESIUM	0.059	0.0003	0.059	0.0072	0.0011	0.0002	0.00008	0.027	0.029	0.064	0.13
CHLORINE	26	0.05	26	0.44	0.36	0.014	0.012	0.32	0.15	0.052	1.4
CHROMIUM	2.6	0.0003	2.6	0.89	0.057	0.0062	0.0009	0.69	3.1	0.35	5.1
COBALT	0.56	0.012	0.58	0.25	0.0005	0.0062	0.0004	0.25	0.091	0.066	0.67
COPPER	3.1	0.0034	3.1	0.71	0.10	0.018	0.0057	1.5	1.8	0.62	4.7
DYSPROSIUM	0.33	<0.0003	0.33	0.071	<0.0002	0.0013	<0.00008	0.026	0.0078	<0.0021	0.11
ERBIUM	0.038	<0.0003	0.039	0.018	<0.0002	0.0002	<0.00008	0.0030	0.0026	<0.0021	0.027
EUROPIUM	0.031	<0.0003	0.031	0.011	<0.0002	0.0001	<0.00008	0.015	0.0052	<0.0021	0.034
FLUORINE	23	0.13	23	1.5	0.036	0.014	0.0027	2.8	0.088	0.43	4.9
GADOLINIUM	0.049	<0.0003	0.049	0.012	<0.0002	0.0002	<0.00008	0.0062	0.010	<0.0021	0.031
GALLIUM	0.20	0.0008	0.20	0.22	0.0014	0.0042	0.0003	0.29	0.55	0.84	1.1
GERMANIUM	0.28	0.0019	0.28	0.047	0.0007	0.0022	0.0003	0.087	0.23	0.23	0.60
GOLD	<0.026	<0.0003	<0.026	<0.0017	<0.0002	<0.00001	<0.00008	<0.0006	<0.0026	<0.0021	<0.0072
HAFNIUM	0.069	<0.0003	0.069	0.096	<0.0002	0.0004	<0.00008	0.036	<0.0026	<0.0021	0.14
HOLMIUM	0.015	<0.0003	0.016	0.0052	<0.0002	0.00004	<0.00008	0.0019	<0.0026	<0.0021	0.013
IODINE	0.31	<0.0003	0.31	0.0060	0.0046	0.0002	0.00008	0.0037	<0.0026	<0.0021	0.019
IRIDIUM	<0.026	<0.0003	<0.026	<0.0017	<0.0002	<0.00001	<0.00008	<0.0006	<0.0026	<0.0021	<0.0072
IRON	>1792	0.15	>1790	>168	0.59	>1.5	0.23	>62	179	37	>450
LANTHANUM	0.74	0.0027	0.74	0.15	0.0025	0.0026	0.0002	0.054	0.029	0.0062	0.24
LEAD	0.17	0.0024	0.17	0.013	0.027	0.0062	0.0004	0.25	0.24	0.021	0.56
LITHIUM	2.4	0.0032	2.4	1.2	0.0028	0.062	0.0019	5.4	0.042	0.0041	6.7
LUTETIUM	0.013	<0.0003	0.013	0.0074	<0.0002	0.00004	<0.00008	0.0009	<0.0026	<0.0021	0.013
MAGNESIUM	>2560	6	>2570	>168	4.5	>1.5	2.1	>62	79	35	>340
MANGANESE	10	0.032	10	~ 42	0.077	~0.51	0.010	~7.5	4.7	0.95	~56

* All flows in lb/hr.

TABLE 4-6 - TRACE ELEMENT FLOWS* AND MATERIAL BALANCE RESULTS AROUND STATION III FROM SPARK SOURCE MASS SPECTROMETRY ANALYSES (Cont.)

ELEMENT	COAL	ASH SLUICE H_2O	Σ IN	BOTTOM ASH	BOTTOM ASH SLUICE H_2O	ECON ASH	ECON ASH SLUICE H_2O	CYCLONE ASH	FLUE GAS SOUTH DUCT.	FLUE GAS NORTH DUCT.	Σ OUT
MERCURY	<0.026	--	<0.026	<0.0017	--	<0.00001	--	<0.0006	--	--	<0.0023
MOLYBDENUM	1.3	0.0037	1.3	0.59	0.0032	0.0026	0.0012	0.46	0.70	0.19	2.0
NEODYMIUM	2.6	0.0013	2.6	0.91	0.0016	0.020	<0.00006	0.34	0.021	0.014	1.3
NICKEL	2.0	0.009	2.0	0.47	0.0032	0.0043	0.0021	0.31	6.2	0.25	7.3
NIOBIUM	0.64	0.0003	0.64	0.30	<0.0002	0.0028	<0.00008	0.11	0.021	0.014	0.45
OSMIUM	<0.026	<0.0003	<0.026	<0.0017	<0.0002	<0.00001	<0.00008	<0.0006	<0.0026	<0.0021	<0.0072
PALLADIUM	<0.026	<0.0003	<0.026	<0.0017	<0.0002	<0.00001	<0.00008	<0.0006	<0.0026	<0.0021	<0.0072
PLATINUM	<0.026	<0.0003	<0.026	<0.0017	<0.0002	<0.00001	<0.00008	<0.0006	<0.0026	<0.0021	<0.0072
POTASSIUM	205	4.8	210	~81	3.2	~7.4	1.6	~15	42	33	~180
PRASEODYMIUM	0.61	<0.0003	0.61	0.082	<0.0002	0.0017	<0.00008	0.030	0.0078	0.0021	0.12
RHENIUM	<0.026	<0.0003	<0.026	<0.0017	<0.0002	<0.00001	<0.00008	<0.0006	<0.0026	<0.0021	<0.0072
RHODIUM	<0.026	<0.0003	<0.026	<0.0017	<0.0002	<0.00001	<0.00008	<0.0006	<0.0026	<0.0021	<0.0072
RUBIDIUM	0.54	0.0050	0.54	0.067	0.0093	0.0035	0.0036	0.14	0.52	0.72	1.5
RUTHENIUM	<0.026	<0.0003	<0.026	<0.0017	<0.0002	<0.00001	<0.00008	<0.0006	<0.0026	<0.0021	<0.0072
SAMARIUM	0.064	<0.0003	0.064	0.014	<0.0002	0.0003	<0.00008	0.012	<0.0026	<0.0021	0.031
SCANDIUM	0.97	<0.0003	0.97	1.3	<0.0002	0.0025	<0.00008	0.21	<0.0026	<0.0021	1.6
SELENIUM	0.69	0.011	0.70	0.032	0.0043	0.0007	0.0037	0.054	2.0	0.27	2.4
SILVER	0.046	0.0005	0.047	0.024	0.0043	0.00004	0.0002	0.0017	0.16	<0.0021	0.19
SODIUM	>2560	34	>2590	>168	23	>4.5	11	>62	78	62	>410
STRONTIUM	110	0.37	110	~47	0.55	~1.2	0.33	~60	7.5	9.7	~130
TANTALUM	<0.026	0.0008	<0.026	0.044	0.0004	0.0002	0.00008	0.0075	0.0078	0.0041	0.064
TELLURIUM	0.026	0.0005	0.026	0.0087	<0.0002	0.00002	<0.00008	0.0010	0.023	0.0021	0.035
TERBIUM	0.023	<0.0003	0.023	0.0089	<0.0002	0.00008	<0.00008	0.0050	<0.0026	<0.0021	0.039
THALLIUM	<0.028	<0.0003	<0.028	<0.0017	0.0005	<0.00001	<0.00008	0.0050	0.075	<0.0021	0.085
THORIUM	0.28	<0.0003	0.28	0.22	<0.0002	0.0020	<0.00008	0.031	<0.0026	0.0021	0.31
THULIUM	0.015	<0.0003	0.016	0.0044	<0.0002	0.00004	<0.00008	0.0007	<0.0026	<0.0021	0.010
TIN	0.31	0.0008	0.31	0.034	0.0089	0.0003	<0.00008	0.029	1.7	0.56	2.4
TITANIUM	115	0.026	115	~39	0.032	~0.29	0.012	~31	11	3.7	~84
TUNGSTEN	0.77	0.0019	0.77	0.27	0.0005	0.0057	0.0002	0.23	0.031	0.0062	0.54
URANIUM	0.20	<0.0003	0.21	0.18	0.0004	0.0017	<0.00008	0.069	0.010	0.006	0.27
VANADIUM	3.3	0.0021	3.3	1.4	0.0018	0.013	0.0027	1.1	5.2	0.56	8.3
YTTERBIUM	0.059	<0.0003	0.059	0.035	<0.0002	0.0003	<0.00008	0.0062	<0.0026	<0.0021	0.047
YTTRIUM	1.6	0.0003	1.6	0.72	0.0004	0.012	0.00008	0.75	0.10	0.019	1.6
ZINC	0.16	0.021	0.13	0.034	0.18	0.0007	0.0070	0.34	3.4	1.1	5.1
ZIRCONIUM	4.4	0.0008	4.4	1.0	0.0007	0.0095	0.00008	0.69	0.21	0.039	2.0

* All flows in lb/hr.

5.0 DISCUSSION

The three power stations considered in this study each utilize a different type of particulate control, specifically venturi wet scrubbers, hot side electrostatic precipitator and cyclones. A comparison of the annual trace element stack emissions from these units normalized to 1000 MW generating capacity is presented in Table 5-1. While the variations in emission levels among the three stations are indicative of the control devices other factors such as coal composition and boiler design also contribute to these differences.

The quantity of an element leaving a generating station in each of the various exiting ash streams is dependent on several factors including:

(1) its concentration in the coal,

(2) station boiler configuration and load,

(3) flue gas emission control devices employed, and

(4) the properties of the element and its compounds.

The first factor is a function of the type and source of the coal. The last three influence the fractional distribution among the various exiting ash streams of the elements which enter the station with the coal. The distribution of the total ash among these streams is dictated by the boiler configuration and the collection efficiency of the flue gas particulate control devices. The effect of the individual properties of the elements on their distribution may be elucidated by comparing the distribution of the elements to the total ash distribution.

TABLE 5-1

TRACE AND MINOR ELEMENT STACK EMISSION

(lb/yr-1000 MW)

Element/Station Coal Type Emission Control	Station I Sub-bituminous Venturi Scrubber	Station II Sub-bituminous Electrostatic Precipitator	Station III Lignite Cyclone
Aluminum	390,000	350,000	6,900,000
Antimony	41	33	1,800
Arsenic	500	8.2	11,000
Barium	9,800	<3,000	<70,000
Beryllium	29	<50	280
Boron	16,000	10,000	630,000
Cadmium	190	18	650
Calcium	1,300,000	610,000	17,000,000
Chlorine	430,000	330,000	410,000
Chromium	18,000	6,500	41,000
Cobalt	310	170	2,900
Copper	1,400	1,400	20,000
Fluorine	20,000	31,000	350,000
Iron	210,000	110,000	8,800,000
Lead	1,200	670	3,500
Magnesium	210,000	90,000	4,200,000
Manganese	5,300	2,000	68,000
Mercury	530	190	960
Molybdenum	8,600	350	33,000
Nickel	2,400	3,300	30,000
Selenium	410	1,400	3,300
Silver	17	4.1	<40
Sulfur	28,000,000	27,000,000	83,000,000
Titanium	19,000	24,000	190,000
Uranium	140	35	1,400
Vanadium	9,800	2,900	28,000
Zinc	6,000	940	33,000
Fly Ash	3,900,000	2,900,000	97,000,000

In the following sections, the differences in boiler configuration and flue gas particulate control among the steam stations and the accompanying effects on the ash distribution are discussed. The elements are classified roughly according to their distributions in the exit ash streams relative to the distribution of the total coal ash. In conclusion, the implications of this data with respect to other types and sources of coal are examined and the findings of this study are compared with results of other investigations.

5.1 Coal Ash Distribution

The trace and minor constituents entering the power stations with the coal are distributed among the following exit ash streams:

(1) fly ash or vapor phase in the flue gas
(2) bottom ash
(3) scrubber ash (Station I)
precipitator ash (Station II)
cyclone ash (Station III)

In all three cases, the economizer ash was an extremely small stream and, therefore, not considered. It was combined with bottom ash at Station II because the two were sluiced together with pyrites from the mills and separate samples were not available.

At the three stations, the distribution of the total ash from the coal among these streams is as follows:

TABLE 5-2

DISTRIBUTION OF THE COAL ASH

AMONG THE EXIT ASH STREAMS

Stream	Station I	Station II	Station III
Bottom ash	21.3%	22.2%	63.1%
Scrubber ash	78.4%	--	--
Precipitator ash	--	77.1%	--
Cyclone ash	--	--	24.0%
Fly ash	0.3%	0.7%	12.9%

The tangentially-fired boilers at Stations I and II produce approximately the same portion of bottom ash. The cyclonic boiler at Station III yields significantly more bottom ash as is common with this burner design. This separation between bottom ash and fly ash leaving the boiler is the first significant point of fractionation of the coal ash and the accompanying elements. The second major fractionation comes at the flue gas particulate control devices. Stations I and II are again comparable at this point. The venturi wet scrubbers at Station I and the hot side electrostatic precipitators at Station II exhibit collection efficiencies for the fly ash based on the ash distributions given above of 99.6% and 99.1% respectively. The mechanical cyclone collectors at Station III retain approximately 65% of the fly ash from the boiler.

5.2 Element Distributions

The majority of the trace and minor elements contained in coal are associated with the mineral matter which forms the major portion of the coal ash. Unless some mechanism produces a selective partition of the elements during one of the major fractionations of the ash, the elements would be distributed

among the ash streams in the same proportions as the total ash. However, from the examination of the data to follow, it is evident that many of the elements are enriched in some of the ash streams and correspondingly depleted in others.

In the following sections, the distributions of the elements among the ash streams are compared to the total ash distribution for each station and to the corresponding elemental and ash distribution of the other stations. The conclusions drawn are mainly based on the results obtained from the quantitative analyses for 27 elements. The behavior of an additional 23 elements is characterized based on the semiquantitative spark source mass spectrometry survey results.

5.2.1 Fly Ash in the Flue Gas

The percent of the 27 elements exiting the stations in the fly ash and flue gas are listed in Table 5-3. The total ash percents in the flue gas are 0.3%, 0.7% and 12.9% for Stations I, II and III respectively. These percents are also presented graphically in Figure 5-1. The total ash percents in the flue gas are indicated by vertical lines color coded for each plant. The crossing of a total ash line and an elemental bar of the same color indicates enrichment of that element in the fly ash and flue gas. The elements in Figure 5-1 are approximately arranged in order of decreasing enrichment in the flue gas plus fly ash. This order will be retained in the discussions of the other ash streams in the following sections.

Enrichment in the flue gas at all three stations (arsenic at two of the three stations) is indicated for:

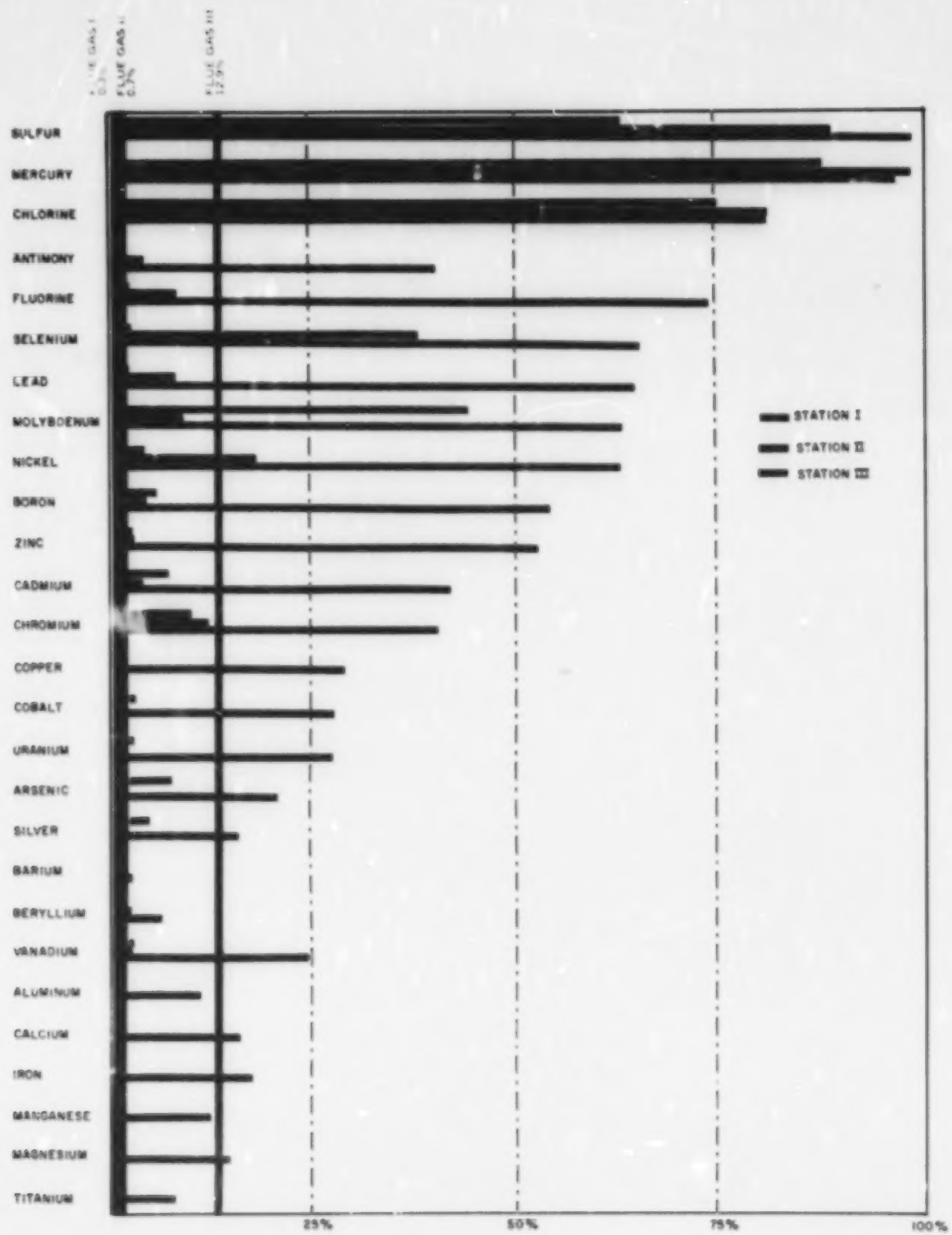


FIGURE 5.1
FRACTIONS OF ELEMENTS
DISCHARGED WITH FLUE GAS

TABLE 5-3

FRACTION OF ELEMENTS ENTERING WITH COAL DISCHARGED IN FLUE GAS FOR SAMPLED STATIONS

Element	Station I Flue Gas (0.3%)	Station II Flue Gas (0.7%)	Station III Flue Gas (12.9%)
Aluminum	0.25	0.7	11.2
Antimony	0.61	3.9	77.9
Arsenic	7.5	0.05	20.5
Barium	<0.84	<0.09	< 1.6
Beryllium	0.65	<2.0	6.5
Boron	5.9	4.7	54.1
Cadmium	7.0	<3.8	41.1
Calcium	0.85	0.8	16.6
Chlorine	75.0	80.2	80.0
Chromium	9.9	12.4	40.3
Cobalt	2.6	1.5	28.5
Copper	0.66	0.8	28.9
Fluorine	2.0	7.6	74.0
Iron	0.63	0.8	17.5
Lead	1.9	7.5	64.6
Magnesium	1.2	0.8	14.8
Manganese	0.38	1.2	12.5
Mercury	86.8	97.9	96.1
Molybdenum	43.2	9.4	63.0
Nickel	4.1	18.2	62.8
Selenium	2.2	27.7	65.4
Silver	4.7	1.3	<15.9
Sulfur	62.2	87.8	98.1
Titanium	0.30	0.6	7.9
Uranium	2.0	1.5	27.6
Vanadium	2.5	2.4	24.9
Zinc	2.5	2.6	52.7

sulfur	lead	chromium
mercury	molybdenum	copper
chlorine	nickel	cobalt
antimony	boron	uranium
fluorine	zinc	arsenic
selenium	cadmium	silver
vanadium		

The remainder of the elements exit the stack in the same proportions as the ash. These include:

barium	aluminum	manganese
beryllium	calcium	magnesium
iron	titanium	

5.2.2 Bottom Ash

At all of the stations, the bottom ash was sluiced to settling ponds. During the course of the sluicing some of the elements are leached from the ash by the sluice water. The measured bottom ash trace element content was corrected for this loss. These corrections were insignificant in most cases and are described in detail in Volumes II, III and IV. The sluice ash at Station II includes not only bottom ash but also pyrites from the mills and economizer ash. The quantities of both are small enough that their effect on the results may be considered negligible.

The corrected fractional discharge in percent for each element with the bottom ash at each of the stations is listed in Table 5-4. The fractions of the coal ash discharged as bottom ash were 21.3% for Station I, 22.2% for Station II and 63.1% for Station III. Discharge values for individual elements smaller than these values indicate depletion of that element in

TABLE 5-4

FRACTION OF ELEMENTS ENTERING WITH COAL DISCHARGED IN BOTTOM ASH OR SLUICE ASH FOR SAMPLED STATIONS

Element	Station I Bottom Ash (21.3%)	Station II Sluice Ash (22.2%)	Station III Bottom Ash (63.1%)
Aluminum	18.0	20.5	67.2
Antimony	9.9	2.7	15.9
Arsenic	5.0	0.8	16.9
Barium	15.4	16.0	64.9
Beryllium	15.7	16.9	58.2
Boron	7.9	12.1	21.0
Cadmium	8.9	<15.7	26.8
Calcium	15.1	18.5	60.3
Chlorine	8.3	16.0	12.2
Chromium	10.7	13.9	44.2
Cobalt	15.5	15.6	48.0
Copper	12.4	12.7	34.1
Fluorine	0	1.1	< 1.1
Iron	20.4	27.9	61.8
Lead	3.1	10.3	< 7.8
Magnesium	17.7	17.2	62.1
Manganese	13.6	17.3	62.5
Mercury	0.78	2.1	< 0.8
Molybdenum	8.4	12.8	16.3
Nickel	18.3	13.6	22.7
Selenium	0	1.4	2.3
Silver	9.5	3.2	22.0
Sulfur	0	3.4	0.09
Titanium	20.6	21.1	69.2
Uranium	50.1	18.0	29.8
Vanadium	16.3	15.3	60.9
Zinc	4.4	29.4	13.3

the bottom ash. Figure 5-2 provides a graphical presentation of this elemental fraction data. The format is the same as that used in Figure 5-1. Depletion of an element in the bottom ash of a station is indicated by the failure of the total ash line and an element bar of the same color to intersect. In general, the elements listed as enriched in the flue gas exhibit depletion in the bottom ashes. Those elements which followed the total ash distribution in the flue gas continue to do so in the bottom ash.

5.2.3 Precipitator, Scrubber and Cyclone Ash

The fractions of the elements in the scrubber ash (Station I), precipitator ash (Station II) and cyclone ash (Station III) are presented in Table 5-5 and Figure 5-3. These presentations follow the same schemes as used in Sections 5.2.1 and 5.2.2. The element fractions are similar to the total ash fractions for most of the elements. Sulfur, mercury and chlorine are markedly depleted in these ash streams. These three elements appear to be leaving the stations predominantly as gaseous species.

5.2.4 Element Distributions Based on Semiquantitative SSMS Surveys

The semiquantitative survey results based on spark source mass spectrometry were analyzed in the same fashion as the quantitative data presented in the previous sections. The conclusions drawn in the following discussion must be considered in the perspective of the accuracy limitations of the technique employed. Due to the scatter in the data, enrichment and depletion of some elements in the flue gas and bottom ash reflect this variability.

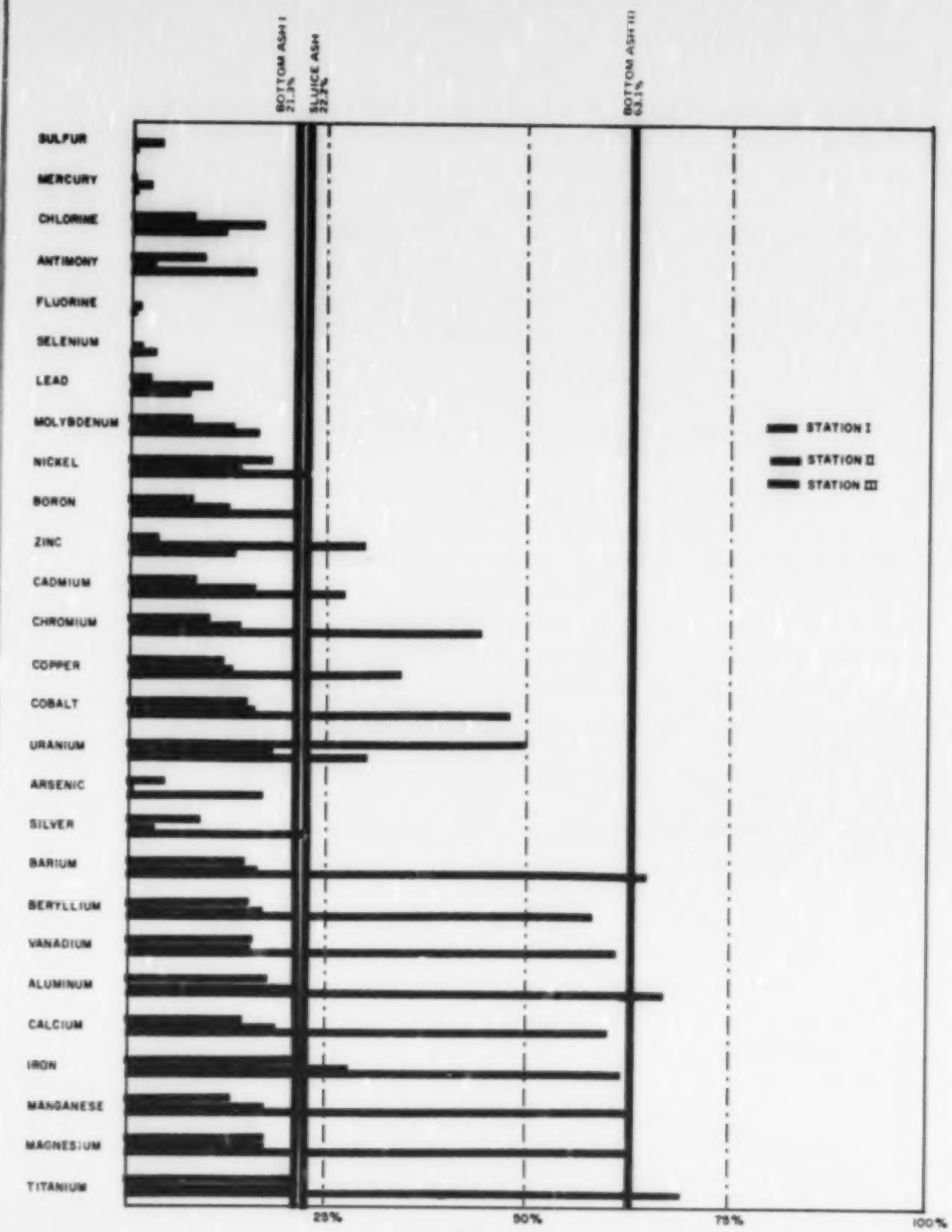


FIGURE 5.2
FRACTIONS OF ELEMENTS
DISCHARGED WITH BOTTOM ASH
OR SLUICE ASH

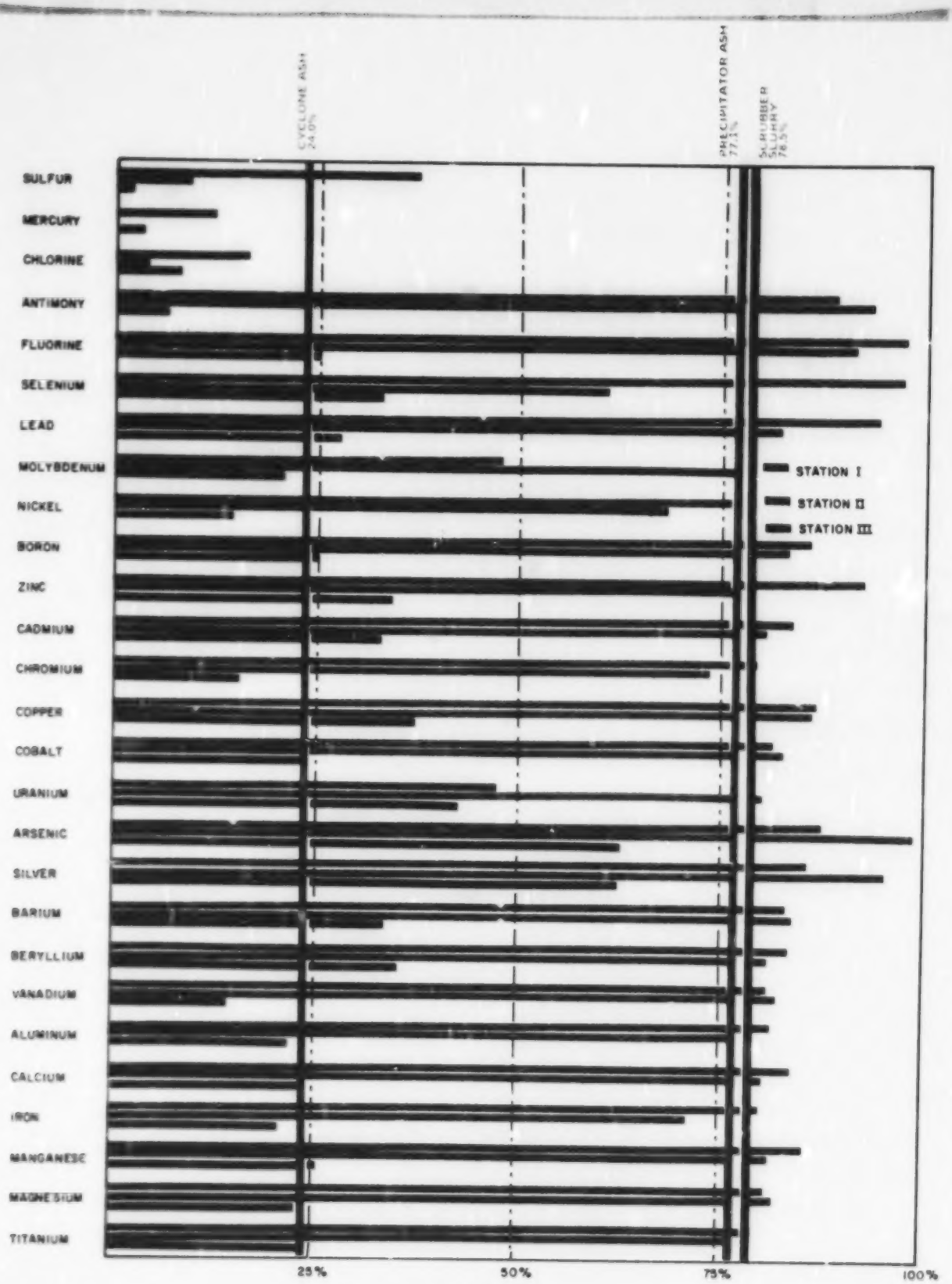


FIGURE 5.3
FRACTION OF ELEMENTS
DISCHARGED WITH SCRUBBER SLURRY,
PRECIPITATOR ASH, OR CYCLONE ASH

TABLE 5-5

FRACTION OF ELEMENTS ENTERING WITH COAL DISCHARGED IN ECONOMIZER ASH PLUS SCRUBBER SLURRY OR CYCLONE ASH OR PRECIPITATOR ASH FOR SAMPLED STATIONS

Element	Station I Economizer Ash & Scrubber Slurry (78.5%)	Station II Precipitator Ash (77.1%)	Station III Economizer Ash & Cyclone Ash (24.0%)
Aluminum	81.7	78.8	21.6
Antimony	89.4	93.4	6.2
Arsenic	87.6	99.1	62.6
Barium	83.6	83.9	33.3
Beryllium	83.8	81.0	35.0
Boron	86.3	83.2	24.8
Cadmium	84.2	80.5	32.5
Calcium	84.1	80.7	23.1
Chlorine	16.7	3.8	7.6
Chromium	79.4	73.7	15.4
Cobalt	81.8	82.9	23.4
Copper	87.0	86.5	37.2
Fluorine	98.0	91.3	25.0
Iron	80.0	71.3	20.7
Lead	94.9	82.2	27.7
Magnesium	81.1	82.0	23.1
Manganese	85.9	81.5	25.2
Mercury	12.5	0	3.1
Molybdenum	48.4	77.8	20.9
Nickel	77.6	68.2	14.3
Selenium	97.8	60.9	32.4
Silver	86.1	95.5	62.2
Sulfur	37.8	8.8	1.8
Titanium	79.1	78.3	23.0
Uranium	47.8	80.5	12.4
Vanadium	81.1	82.3	14.1
Zinc	93.0	68.0	34.2

The individual element fractions in the flue gas and bottom ash along with the corresponding total ash fractions for the three plants are presented graphically in Figures 5-4 and 5-5 respectively. The presentation format and color code follow that used in the previous figures.

The elements enriched in the flue gas are:

tin	gallium
rubidium	bismuth
tellurium	thallium
cesium	bromine

The remainder of the elements appear to be more or less evenly distributed. These include:

europium	lanthanum	cesium
tantalum	strontium	yttrium
holmium	zirconium	tungsten
phosphorus	praseodymium	neodymium
gadolinium	niobium	

An analogous pattern is reflected in the element fractions in the bottom ash where those elements enriched in the flue gas demonstrate a corresponding depletion in the bottom ash. Elements for which the SSMS data were inconclusive are not included in the above analysis.

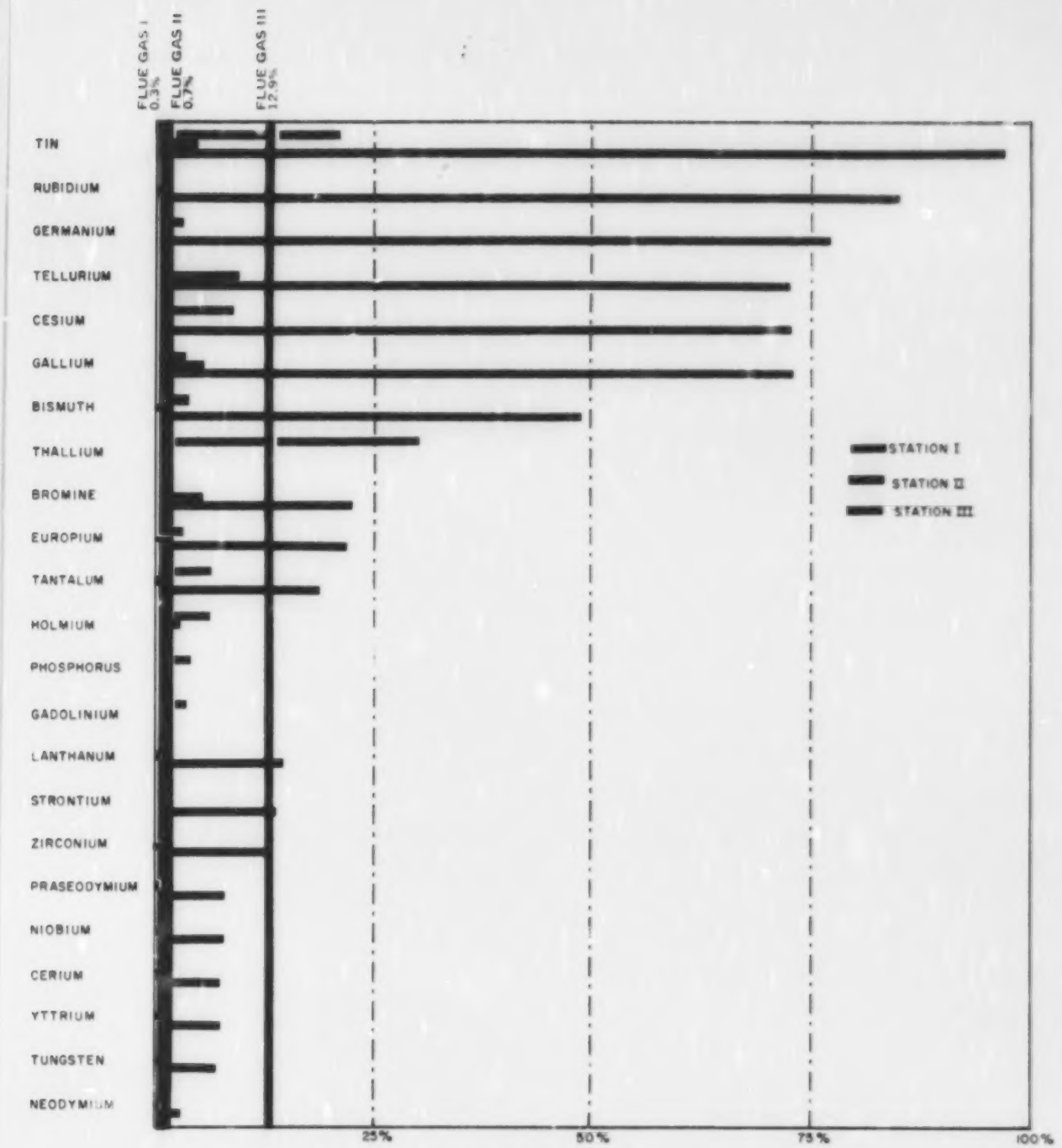


FIGURE 5.4
FRACTIONS OF ADDITIONAL
ELEMENTS FROM SSMS ANALYSIS
DISCHARGED WITH FLUE GAS

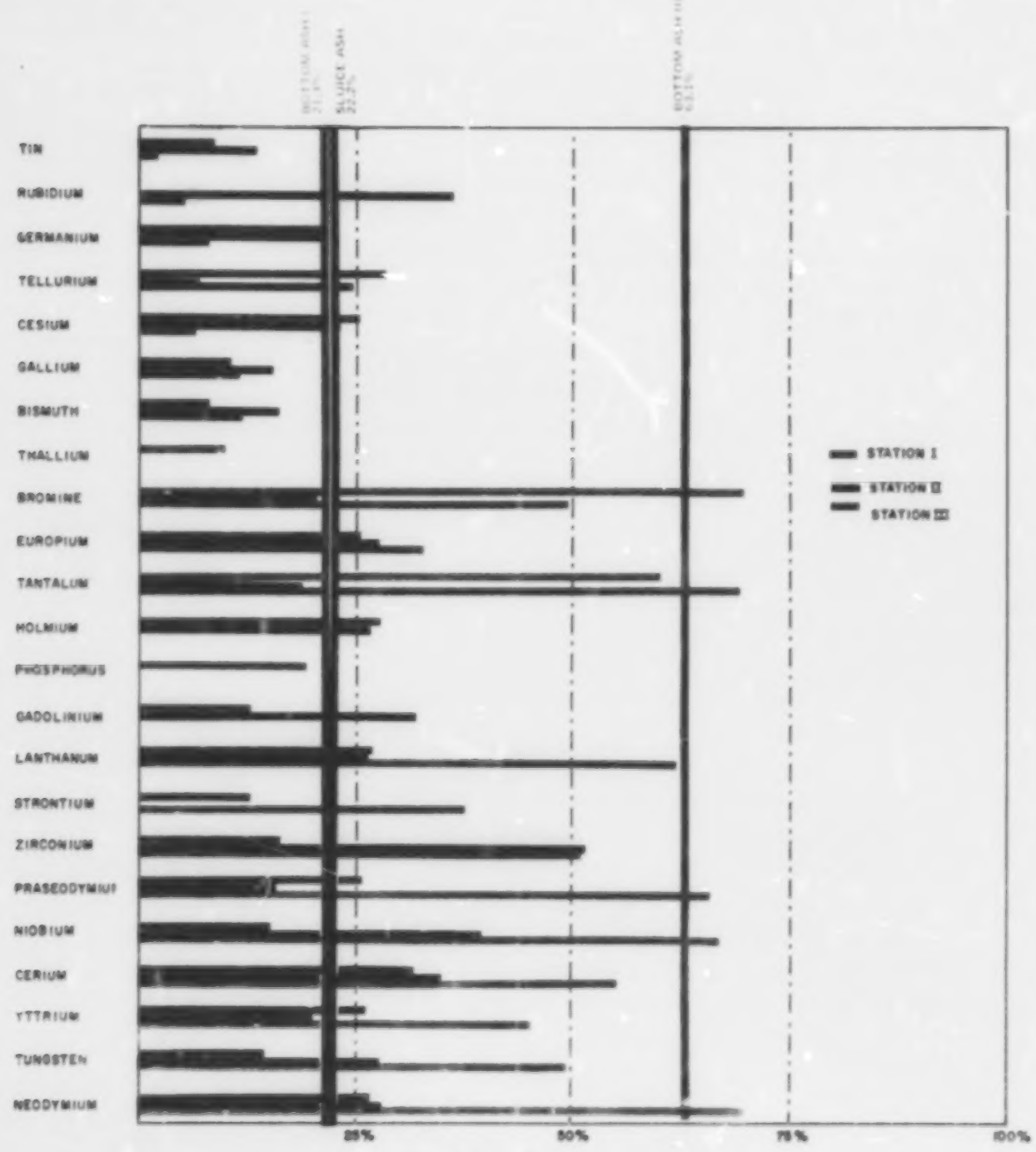


FIGURE 5.5
FRACTIONS OF ADDITIONAL
ELEMENTS FROM SSMS ANALYSIS
DISCHARGED WITH BOTTOM ASH, OR SLUICE ASH

5.3 Comparison of the Stations I, II and III Coals With the Trace Element Content of Other U.S. Coals

The concentrations of 27 elements measured in the coals from Stations I, II and III are summarized in Table 5-6. The arrangement of the elements follows the degree of enrichment in the flue gas discussed in Sections 5.2 and 5.3. Also listed in Table 5-6 are average values reported in 82 Illinois Basin coal samples comprising deposits in Illinois, Indiana, and Western Kentucky (RU-019). It can be seen that the trace element levels for the three western coals analyzed in this study are in most cases much lower than the average levels found in other coals. This is especially true for chlorine, while the levels for fluorine and copper are of the same order of magnitude The lower trace element content does not necessarily mean lower emissions per unit of electrical power generated due to the lower heating value of western coal.

Stations with similar boiler configurations and flue gas particulate controls to the stations studied should experience similar elemental behavior. However, the trace element contents of coals vary widely as evidenced by the review data in Appendix A. The conclusions drawn from the enrichment and depletion patterns in the ash streams about the elemental behavior during the coal combustion are of a qualitative nature. Quantitative assessment of emission levels must be on a case-by-case basis with experimentally determined emissions rather than general predictions until a great deal more data is accumulated.

5.4 Enrichment Mechanism

The enrichment of certain elements in the fly ash and flue gas of the various stations can be explained by the volatilization of these elements or their compounds in the fire box of

TABLE 5-6

COMPARISON OF STATIONS I, II & III COAL WITH OTHER U.S. COALS

Element	Station I lb/10⁶ BTu	Station I ppm dry weight	Station II lb/10⁶ BTu	Station II ppm dry weight	Station III lb/10⁶ BTu	Station III ppm dry weight	Average of (Illinois Basin) 82 Coals lb/10⁶ BTu	Average of (Illinois Basin 82 Coals ppm dry weight
Sulfur	760	0.72%	420	0.49%	1480	1.44%	2750	3.51%
Mercury	0.014	0.13	0.012	0.14	0.0075	0.074	0.016	0.21
Chlorine	4.6	44	0.80	9.3	5.6	55	120	0.15%
Antimony	0.056	0.53	0.014	0.16	0.041	0.40	0.11	1.43
Fluorine	15	140	5.7	67	5.8	57	4.7	59.3
Selenium	0.23	2.2	0.14	1.6	0.13	1.3	0.16	1.99
Lead	0.44	4.2	0.20	2.3	0.087	0.86	3.1	39.83
Molybdenum	0.42	4.0	0.055	0.64	0.20	2.0	0.62	7.96
Nickel	0.95	9.0	0.18	2.1	0.55	5.4	1.7	22.35
Boron	5.4	51	2.6	31	15	150	8.9	113.79
Zinc	2.5	24	0.35	4.1	0.79	7.8	25	313.04
Cadmium	0.019	0.18	<0.008	<0.1	0.020	0.20	2.3	2.89
Chromium	2.2	21	0.79	9.3	1.3	13	1.1	14.10
Copper	3.6	34	2.6	31	1.1	10.5	1.1	14.09
Cobalt	0.22	2.1	0.13	1.5	0.076	0.75	7.2	9.15
Uranium	0.14	1.3	0.076	0.89	0.15	1.5		
Arsenic	0.087	0.83	0.21	2.5	0.81	8.0	1.2	14.9
Silver	0.0047	0.045	0.0041	0.048	0.0035	0.034		
Barium	14	130	39	460	45	440		
Beryllium	0.086	0.82	0.025	0.29	0.061	0.60	0.13	1.72
Vanadium	5.4	51	1.7	20	1.5	15	2.6	33.13
Aluminum	2420	2.3%	610	0.71%	750	0.74%	960	1.22%
Calcium	1850	1.76%	930	1.09%	1400	1.38%	580	0.74%
Iron	420	0.40%	180	0.21%	760	0.75%	1610	2.06%
Manganese	18	170	2.0	24	8.0	79	4.2	53.16
Magnesium	300	0.29%	130	0.15%	380	0.37%	39	0.05%
Titanium	120	1100	48	565	35	350	47	0.06%
BTU/lb (dry)	--	9511	--	11708	--	9838	--	12750
Ash (dry basis)	21700	20.6%	6150	7.2%	12680	12.4%	8850	11.28%
Moisture	38800	27.0%	35200	29.2%	59300	36.8%	8730	10.02%

the boiler. This volatilization provides the mechanism for the selective partitioning of elements during the fractionation of the ash between fly ash and bottom ash. The volatilized elements or their compounds can subsequently

(1) remain gaseous
(2) recondense partially, or
(3) recondense completely.

In the first case, a high percentage of an element incoming with the coal will be discharged through the stack unless the flue gas control devices are designed for their collection. This behavior seems to be exhibited by these elements:

(1) sulfur
(2) mercury, and
(3) chlorine.

Partial or complete condensation will lead to an increase in the concentration of these elements in the fine particulate fraction of the fly ash. Condensation can occur by nucleation or deposition on available surfaces. At the relatively low residence times between volatilization and condensation, any nucleation that occurs will result in small particles. Deposition on the fly ash particles will be surface area dependent. This also will result in increased concentrations in the small particulates since the specific surface area is greater for the smaller ash particles.

This trace element concentration dependence on the fly ash particle size was also observed by Davison, Natusch and

Wallace (DA-105). Elements found to increase markedly in concentration as function of decreasing particle size were Pb, Tl, Sb, Cd, Se, As, Zn, Ni, Cr and S. The concentration dependence was found to be inversely proportional to the average particle diameter.

Similar results were found by Lawasani and West (LA-146). Elements enriched in the fine particulate matter were As, Cu, Mo, Pb, Se, Sn and Zn. No concentration dependence was found for Al, Fe, Nb, Rb, Sr, Y and Zr.

Gladney, Gordon and Zoller (GL-035) measured the enrichment of elements in urban aerosols and compared their concentration with the average in the earth crust. Enrichment factors of greater then ten times over average crustal abundance for Tl, Cr, Ni, Cr, Zn, As, Cd, Sn, Pb, Se, Cl and Br were measured. The authors established correlations with enrichment patterns in coal fly ash, municipal incinerator fly ash and residue fuel oil.

The findings of the present study are compared with those cited above in Table 5-7. Qualitative agreement between the various sources is excellent.

TABLE 5-7

ELEMENT ENRICHMENT IN FINE PARTICULATE MATTER

Sources	Elements Found to be Enriched in Fines or Completely Volatile
Davison[1]	S Sb Se Pb Ni Zn Cd Cr As Tl
Gladney[2]	S Cl Se Pb Ni Zn Cd Cr Cu As Sn Tl Br
Lawasani-West[3]	Sb Se Pb Mo Zn Cu As Sn
This Study	S Hg Cl Sb F Se Pb Mo Ni B Zn Cd Cr Cu Co U As Ag Sn* Rb* Te* Cs* Ga* Bi* Tl* Br*

[1](DA-105)

[2](GL-035)

[3](LA-146)

*Based on SSMS results.

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GL-035 Gladney, Ernest S., et al., "Composition and Size Distributions of Atmospheric Particulate Matter in Boston Area", Env. Sci. Tec. 8(6), 551 (1974).

LA-146 Lawasani, Mohammed Hussain, "Model of Fate of Trace Elements in Coal Fired Power Plant", Summary of Master's thesis.

RU-019 Ruch, R. R., Harold J. Gluskoter, and E. Joyce Kennedy, Mercury Content of Illinois Coals, Environmental Geology Notes No. 43, Urbana, Ill., Illinois State Geological Survey, 1971.

APPENDIX A

SURVEY OF TRACE ELEMENT CONCENTRATIONS IN VARIOUS COALS

Element	Type and/or Origin of Coal	Concentration In Coal or Ash	Remarks	Source
Al	U. S.	Coal: 43-3.0%	Whole coal, X-RF	4
	Anthracite	Ash: 13.2-23.3%		3
	Bituminous	Ash: 2.1-20.6%		3
	Sub-bituminous	Ash: 2.1-18.5%		3
	Lignite	Ash: 2.1-13.8		3
	Illinois Basin	Coal: .43-3.0%	Whole coal, X-RF	4
Sb	West Virginia	Ash: <.004-.023%		2
		100-200 ppm		2
	England, vitrain	Ash <.01-.05%		2
	Ruhr, Germany	Ash: .3% max		2
		Coal: 17 ppm max		2
	Germany	Ash: >1000 ppm		4
		Coal: 10-30 ppm	LTA, NAA	4
	U. S.	Coal: .20-8.90 ppm	LTA, NAA	4
	Illinois Basin	Coal: .20-8.90 ppm		2
		Ash: .05-.1%	Also atmospheric dust .007-.033%	2
As	Germany			2
		Coal:		2
	England	Coke: .0037%		2
	U. S.	Coke: .002-.011%		2
	Germany	Ash: 280-2300 ppm		2
	Sydney, Nova Scotia	Coal: 33-270 ppm		2
		Ash: 10,000 ppm max		
	Germany	Coal: 500 ppm max		

Element	Type and/or Origin of Coal	Concentration In Coal or Ash		Remarks	Source
As (Cont'd)	U. S.	Coal:	.00006-.0016%	13 samples	2
			.0106%	1 sample	
	England	Coal:	0-.0098%		2
	England	Coal:	0-.0220%		2
	France	Coal:	.0415%		2
	Germany, Lower Rhine	Coal:	.08-.2%		2
	Germany, Saarbrück	Coal:	.003%		2
	South Africa	Coal:	.00003-.00103%		2
	South Africa	Coal:	0-.0008%		2
	South Africa	Coal:	Up to .0006%		2
	Pennsylvania, anthracite	Ash:	.0021-.0055%		2
	Pennsylvania, anthracite	Ash:	Up to .01%		2
	North and South Dakota	Ash:	.1-1.0		2
	West Virginia	Ash:	Up to .057%		2
	England, Newcastle	Ash:	.05%		2
	Germany, Newrode	Ash:	.07%		2
	Portugal, anthracite	Ash:	.01-.1%		2
	U. S.	Coal:	50-93.0 ppm	LTA	4
	Illinois Basin	Coal:	1.70-93.0 ppm	LTA, NAA	4
Ba	England			Mine waters	2
	Germany			Mine waters	2
	England			Roof rocks above coal bed	2
	England			Sandstone above coal	2
	England			Barite fissure	2

Element	Type and/or Origin of Coal	Concentration in Coal or Ash		Remarks	Source
Ba (Cont'd)	West Virginia	Ash:	.05-.44%		2
	North Dakota	Ash:	.15%		2
	Alaska, Nenna Field	Ash:	.4-.9%		2
	England	Ash:	0-4.3%		2
	Nova Scotia	Ash:	.0018-.22%		2
	Germany, Newrode	Ash:	.22%		2
	Germany, brown coal	Ash:	.0001%		2
	Germany	Ash:	>.1%		2
	Portugal, anthracite	Ash:	.01-.1%		2
	Spitzenberger	Ash:	.1-.2%		2
	Eastern U. S., anthracite	Ash:	540-1340 ppm	LTA	3
	Western U. S., high vol. bituminous	Ash:	210-4660 ppm	LTA	3
	Interior U. S., low vol. bituminous	Ash:	96-2700 ppm	LTA	3
	Northern Great Plains, medium vol. bituminous	Ash:	230-1800 ppm	LTA	3
	Great Plains, lignite and sub-bituminous	Ash:	550-13900 ppm	LTA	3
Be	Appalachian -Eastern Province:				
	Northern Region:				
	Lower Kittanning bed	Ash:	.0016-.0041%		2
		Coal:	1.6-4.1 ppm		
	Middle Kittanning bed	Ash:	.0016-.014%		2
		Coal:	1.5-4.2 ppm		

Element	Type and/or Origin of Coal	Concentration In Coal or Ash		Remarks	Source
Be (Cont'd)	Southern Region:				
	Alabama	Ash:	.0011-.015%		2
		Coal:	.5-4.6 ppm		2
	Eastern Kentucky	Ash:	.001-.11%		2
		Coal:	.4-31 ppm		2
	Tennessee	Ash:	.0005-.004%		2
		Coal:	.1-11 ppm		2
	Virginia and West Virginia	Ash:	.0007-.007%		2
		Coal:	.2-3.6 ppm		
	Interior Province:				
	Eastern Region:				
	Illinois (total)	Ash:	.0004-.011%		2
		Coal:	.7-6.3 ppm		
	Illinois, Bed 5	Ash:	.0011-.011%		2
		Coal:	1-3.2 ppm		2
	Illinois, Bed 6	Ash:	.0004-.0044%		2
		Coal:	.7-4 ppm		
	Indiana (total)	Ash:	.0032-.017%		2
		Coal:	1.5-12 ppm		
	Western Kentucky (total)	Ash:	.0004-.0093%		2
		Coal:	.5-9.5 ppm		
	Western Kentucky, Bed 9	Ash:	.0013-.0057%		2
		Coal:	1.7-4.3 ppm		

Element	Type and/or Origin of Coal	Concentration In Coal or Ash		Remarks	Source
Be (Cont'd)	Western Region:				
	McAlister Basin	Ash:	.0001- .003%		2
		Coal:	<.1-2.9 ppm		
	All other	Ash:	.0003- .011%		2
		Coal:	.5-5.1 ppm		
	Northern Great Plains:				
	Jurassic and Cretaceous	Ash:	.0015-.0094%		2
		Coal:	2.7-5.8 ppm		
	Paleocene and Eocene	Ash:	<.0001-.013%		2
		Coal:	<.1-9.1 ppm		
	Rocky Mountains:				
	Sweetwater County, Wyoming	Ash:	.0003- .038%		2
		Coal:	.1-13 ppm		
	All other	Ash:	<.0001-.062%		2
		Coal:	<.1-31 ppm		
	Northern Great Plains	Coal:	1.5 ppm avg		2
	Eastern Interior	Coal:	2.5 ppm		2
	Appalachian	Coal:	2.5 ppm		2
	England and Germany	Ash:	.001-1.0%		2
	France	Coal:			2
	Pennsylvania, anthracite	Ash:	.001- .009%		2
	Texas, Colorado, North and South Dakota	Ash:	.1-1.0%		2
	West Virginia	Ash:	.0007-.01087%		2
	Belgium	Ash:	.002-.05		2

Element	Type and/or Origin of Coal	Concentration In Coal or Ash		Remarks	Source
Be (cont'd)	Germany, Newrode	Ash:	.001%		2
	Germany	Ash:	.0013%		2
	England, Newcastle	Ash:	.0036%		2
	England, vitrain	Ash:	.005-.01%		2
	Nova Scotia	Ash:	.0014%		
	Portugal, anthracite	Ash:	up to .01%		2
	Russia	Ash:	0-.1%		4
	U. S.	Coal:	.20-4.00 ppm	HTA, OE-DR, OE-P	1
	Northern Great Plains	Ash:	<.0001-.03%		
		Coal:	<.1-8.2 ppm		3
	Eastern U. S., anthracites	Ash:	6-11 ppm	LTA	
	Western U. S., high vol. bituminous	Ash:	4-60 ppm	LTA	3
	Interior U. S., low vol. bituminous	Ash:	6-40 ppm	LTA	3
	Northern Great Plains, medium vol. bituminous	Ash:	4-31 ppm	LTA	3
	Great Plains, lignite and sub-bituminous	Ash:	1-28 ppm	LTA	3
	Illinois Basin	Coal:	.50-4.0 ppm	HTA, OE-DR, OE-P	4
B	Texas, Colorado, North and South Dakota	Coal:	>.1%		2
	Germany	Ash:			2
	New Zealand	Coal:			2

Element	Type and/or Origin of Coal	Concentration In Coal or Ash		Remarks	Source
B (Cont'd)	Poland	Coal:			2
	Northern Great Plains	Ash:	.005-.65%		2
		Coal:	11o ppm		
	West Virginia	Ash:	.008-.096%		2
	North Dakota	Ash:	.21%		2
	Eastern Interior	Coal:	96 ppm		2
	Appalachian	Coal:	25 ppm		2
	Nova Scotia	Ash:	.0052-.022%		2
	Germany, Newrode	Ash:	.09%		2
	England, Newcastle	Ash:	.31%		2
	England, vitrain	Ash:	.02-.3%		2
	Spitzbergen	Ash:	.1-2.0%		2
	Portugal, anthracite	Ash:	.001-1.0%		2
	New Zealand	Ash:	up to 1.51%		2
	Austria	Ash:	up to .46%		2
	England	Coal:	2-140 ppm		2
	South Africa	Coal:	11-60 ppm		2
	U. S.	Coal:	5-224 ppm	NTA, OE-DR	4
	Eastern U. S., anthracite	Ash:	63-130 ppm	LTA	3
	Western U. S., high vol. bituminous	Ash:	90-2800 ppm	LTA	3
	Interior U. S., low vol. bituminous	Ash:	76-180 ppm	LTA	3
	Northern Great Plain, medium vol. bituminous	Ash:	74-780 ppm	LTA	3

Element	Type and/or Origin of Coal		Concentration in Coal or Ash	Remarks	Source
	S (Cont'd)	Great Plains, lignite and sub-bituminous	Ash: 320-1900 ppm	LTA	3
		Illinois Basin	Coal: 12-224 ppm	LTA, OE-DA	4
	Cd	U. S.	Coal: .10-65.0 ppm	LTA, AA	4
		Illinois Basin	Coal: .10-65.0 ppm	LTA, AA	4
	Ca	U. S.	Coal: .05-2.67%	Whole coal, X-RF	4
		Anthracite	Ash: .14-2.86%		3
		Bituminous	Ash: .50-25.7%		3
		Sub-bituminous	Ash: 1.57-37.1%		3
		Lignite	Ash: 8.86-37.1%		3
		Illinois Basin	Coal: .05-2.67%	Whole coal, X-RF	4
	Cl	Illinois	Coal: .03-.56%	$AgNO_3$ titrate	2
		Western U. S.	Coal: .01-.46%	O_2 bomb and titrate	2
		Poland	Coal: 0-.19%		2
		England	Coal: .01-1.0%		2
		England	Coal:		2
		U. S.	Coal: .01-.54%	Whole coal, X-RF	4
		Illinois Basin	Coal: .01-.54%	Whole coal, X-RF	4
	Cr	Northern Great Plains	Ash: <.0001-.03%		2
			Coal: 7 ppm		

Element	Type and/or Origin of Coal	Concentration in Coal or Ash		Remarks	Source
Cr (Cont'd)	North Carolina, peat	Ash:	.019-.023%		2
	Pennsylvania, anthracite	Ash:	.001-.01%		2
	Pennsylvania, Cambria County	Ash:	.027%		2
	Pennsylvania, Washington Co.	Ash:	.013%		2
	Texas, Colorado, North and South Dakota	Ash:	.01- 1%		2
	West Virginia	Ash:	.011- .02%		2
	England	Ash:	.0114-.01771%		2
	England, vitrain	Ash:	.01-.1%		2
	England, Newcastle	Ash:	.03%		2
	England, vitrain	Ash:	up to 1.5%		2
	Germany, Nowrode	Ash:	.014%		2
	Nova Scotia	Ash:	.0016-.0079%		2
	Portugal, anthracite	Ash:	.01- 1%		2
	Spitzbergen	Ash:	.01-.1%		2
	U. S., Eastern Interior	Coal:	20 ppm		2
	Appalachian	Coal:	11 ppm		2
	Japan	Coal:	.03-33 ppm		2
	Germany	Coal:	30 ppm		2
	U. S.	Coal:	4-54 ppm	HTA, OE-DR, OE-P	4
	Eastern U. S., anthracites	Ash:	210-395 ppm	LTA	3
	Western U. S., high vol. bituminous	Ash:	74-315 ppm	LTA	3
	Interior U. S., low vol. bituminous	Ash:	120-490 ppm	LTA	3

Element	Type and/or Origin of Coal	Concentration In Coal or Ash		Remarks	Source
Cr (Cont'd)	Northern Great Plains, medium vol. bituminous	Ash:	30-230 ppm	LTA	3
	Great Plains, lignite and sub-bituminous	Ash:	11-140 ppm	LTA	3
	Illinois Basin	Coal:	4-54 ppm	HTA, OE-DR, OE-P	4
Co	Northern Great Plains	Coal:	2.7 ppm		2
	Eastern Interior, U. S.	Coal:	3.8 ppm		2
	Appalachian	Coal:	5.1 ppm		2
	Northern Great Plains	Ash:	<.0005-.009%		1
	Pennsylvania, anthracite	Ash:	.001-.009%		2
	Texas, Colorado, North and South Dakota	Ash:	.01-1.0%		2
	West Virginia	Ash:	.005-.018%		2
	England, vitrain	Ash:	.01-.03%		2
	Finland, peat	Ash:	<.001-.03%		2
	Germany	Ash:	.2% max		2
	Nova Scotia	Ash:	.0026-.0196%		2
	Portugal, anthracite	Ash:	.01-.1%		2
	Spitzbergen	Ash:	.001-.01%		2
	U. S.	Coal:	1-43 ppm	HTA, OE-DR, OE-P	4
	Northern Great Plains	Coal:	< 4-12 ppm		1
	Eastern U. S., anthracite	Ash:	10-165 ppm	LTA	3
	Western U. S., high vol bituminous	Ash:	12-305 ppm	LTA	3

Element	Type and/or Origin of Coal	Concentration In Coal or Ash		Remarks	Source
Co (Cont'd)	Interior U. S., low vol bituminous	Ash:	26-460 ppm	LTA	3
	Northern Great Plains, medium vol bituminous	Ash:	10-290 ppm	LTA	3
	Great Plains, lignite and sub-bituminous	Ash:	11-310 ppm	LTA	3
	Illinois Basin	Coal:	2-34 ppm	HTA, OE-DR, OE-P	4
Cu	Northern Great Plains	Coal:	15 ppm		2
	Eastern Interior, U. S.	Coal:	11 ppm		2
	Appalachian	Coal:	15 ppm		2
	England	Coal:	1-170 ppm	pyritos	2
	Romania	Coal:	1.87-14.68 gm/ton		2
	New brunswick, Canada, peat	Coal:		300 tons in peat swamp	2
	Northern Great Plains	Ash:	.002-.07%		1
	North Dakota	Ash:	.02%		2
	Pennsylvania, anthracite	Ash:	.001-.01%		2
		Ash:	.03-.07%		
	Texas, Colorado, North and South Dakota	Ash:	.01-.1%		2
	West Virginia	Ash:	.022-.1%		2
	England, Newcastle	Ash:	.06%		2
	England, vitrain	Ash:	.03-.1%		2
	Germany, brown coal	Ash:	up to .001%		2

Element	Type and/or Origin of Coal		Concentration in Coal or Ash	Remarks	Source
Cu (Cont'd)	Germany, Westphalia	Ash:	.016- .054%		2
	Germany	Ash:	.42 max		2
	Portugal, anthracite	Coal:	.001- .01%		2
	U. S.	Coal:	5-61 ppm	LTA, AA, HTA, OE-DR	4
	Northern Great Plains	Coal:	2.6-135 ppm		1
	Eastern U. S., anthracite	Ash:	96-540 ppm	LTA	3
	Western U. S., high vol. bituminous	Ash:	30-770 ppm	LTA	3
	Interior U. S., low vol. bituminous	Ash:	76-850 ppm	LTA	3
	Northern Great Plains, medium vol. bituminous	Ash:	130-560 ppm	LTA	3
	Great Plains, lignite and sub-bituminous	Ash:	58-3020 ppm	LTA	3
	Illinois Basin	Coal:	5-44 ppm	LTA, AA; HTA, OE-DR	4
Y	Western Pennsylvania	Coal:	85 ppm, 167 ppm	2 samples	2
	Vancouver, Washington	Coal:	145-295 ppm		2
	Utah	Coal:	145-295 ppm		2
	Utah	Coal:	40-112 ppm		2
	England	Coal:			2
	Japan	Coal:	100-480 ppm		2
	England	Coal:	0-175 ppm		2
	U. S.	Coal:	25-143 ppm	Whole coal, ISE	4
	Illinois Basin	Coal:	30-143 ppm	Whole coal, ISE	4

Element	Type and/or Origin of Coal	Concentration in Coal or Ash		Remarks	Source
Pa	U. S.	Coal:	34-4.32%	Whole coal, X-RF	4
	Anthracite	Ash:	1.4-7.0%		3
	Bituminous	Ash:	1.4-30.8%		3
	Sub-bituminous	Ash:	2.1-13.3%		3
	Lignite	Ash:	7-23.8%		3
	Illinois Basin	Coal:	.48-4.32%	Whole coal, X-RF	4
Pb	England	Coal:	.024%		2
	England	Coal:	.0001-.0461%	Pyrites	2
	West Virginia	Ash:	.019-.13%		2
	Texas, Colorado, North and South Dakota	Ash:	.01-.1%		2
	Pennsylvania, anthracite	Ash:	.001-.01%		2
	Nova Scotia	Ash:	.0572% ave		2
	England, vitrain	Ash:	.02-.08%		2
	Germany	Ash:	3.1% max		2
	U. S.	Coal:	4-218 ppm	LTA, AA, HTA, GE-SR	4
	Eastern U. S., anthracite	Ash:	41-120 ppm	LTA	3
	Western U. S., high vol. bituminous	Ash:	32-1500 ppm	LTA	3
	Interior U. S., low vol. bituminous	Ash:	23-170 ppm	LTA	3
	Northern Great Plains, medium vol. bituminous	Ash:	52-210 ppm	LTA	3

Element	Type and/or Origin of Coal	Concentration In Coal or Ash		Remarks	Source
Pb (Cont'd)	Great Plains, lignite and sub-bituminous	Ash:	20-165 ppm	LTA	3
	Illinois Basin	Coal:	4-218 ppm	LTA, AA, HTA, OE-DR	4
Mn	West Virginia	Ash:	.012-.18%		2
	Pennsylvania, anthracite	Ash:	.005-.006%		2
	North Dakota	Ash:	.15%		2
	Montana	Ash:	.33%		2
	Alabama	Ash:	.04-.05%	2 analyses	2
	Texas, Colorado, North and South Dakota	Ash:	.1-1.0%		2
	England	Ash:	.08-.18%		2
	England, Newcastle	Ash:	.01%		2
	Germany, Neurode	Ash:	.05%		2
	Germany, Ruhr	Ash:	.6%		2
	Germany, brown coal	Ash:	.35%		2
	Germany	Ash:	2.2% max		2
	Portugal, anthracite	Ash:	.001-1.0%		2
	Nova Scotia	Ash:	.0165-.22%		2
	Spitzbergen	Ash:	.01-.1%		2
	Russia, peat	Ash:	.098-.109%		2
	Russia	Ash:	.0205%		2
	U. S.	Coal:	6-181 ppm	Whole coal, dAA	4
	Eastern U. S., anthracite	Ash:	58-365 ppm	LTA	3

Element	Type and/or Origin of Coal	Concentration in Coal or Ash		Remarks	Source
Mn (Cont'd)	Western U. S., high vol. bituminous	Ash:	31-700 ppm	LTA	3
	Interior U. S., low vol. bituminous	Ash:	40-780	LTA	3
	Northern Great Plains, medium vol. bituminous	Ash:	125-4400 ppm	LTA	3
	Great Plains, lignite and sub-bituminous	Ash:	310-1030 ppm	LTA	3
	Illinois Basin	Coal:	6-181 ppm	Whole coal, NAA	4
Mg	U. S.	Coal:	.01- 25%	Whole coal, X-RF	4
	Anthracite	Ash:	.12-.6%		3
	Bituminous	Ash:	.06-2.4%		3
	Sub-bituminous	Ash:	.30-4.8%		3
	Lignite	Ash:	1.68-8.4%		3
	Illinois Basin	Coal:	.01-.17%	Whole coal, X-RF	4
Hg	West Virginia	Coal:	<.007%		2
		Ash:	<.007- .019% .055% max		
	Western U. S.	Coal:	<.1%		2
	England	Coal tar:	1 part in 1.5 million parts tar		2
	U. S.	Coal:	.02-1.60 ppm	Whole coal, NAA	4
	Illinois Basin	Coal:	.03-1.60 ppm	Whole coal, NAA	4

Element	Type and/or Origin of Coal		Concentration in Coal or Ash	Remarks	Source
Mo	Northern Great Plains	Ash	.0003-.0065%		1
	Texas, Colorado, North and South Dakota	Ash	.1-1.0% max		3
	South Dakota, Harding Co.	Ash	.15%		2
	West Virginia	Ash	.003-.027%		2
	Pennsylvania, anthracite	Ash	.001-.009%		2
	Nova Scotia	Ash	.0018-.0105%		2
	Portugal, anthracite	Ash	.001-.01%		2
	Germany, Newrode	Ash	.007%		2
	England, Newcastle	Ash	.011%		2
	England, vitrain	Ash	.008-.02%		2
	Northern Great Plains	Coal	1.7 ppm		2
	Eastern Interior, U. S.	Coal	4.3 ppm		2
	Appalachian Area	Coal	3.5 ppm		2
	Germany	Coal	21 ppm		2
	Everglade, peat	Coal			2
	U. S.	Coal	1-30 ppm	HTA, OE-DR	4
	Northern Great Plains	Coal	.7-4.9 ppm		1
	Illinois Basin	Coal	1-29 ppm	HTA, OE-DR	4
Ni	Kuznetsk Basin, U.S.S.R.	Coal	.001-.01% .05-1.0%		2
	England, vitrain	Coal	2.36%	1.35 sp. gr.	2
	Durham, England	Ash	.7-8.1%	1.35 sp. gr.	2

Element	Type and/or Origin of Coal		Concentration in Coal or Ash	Remarks	Source
Ni (Cont'd)	Kent, England, vitrain	Ash:	.08-1.3%	1.30 sp. gr.	2
	Yorkshire, England	Ash:	.78%		2
	Northern Great Plains	Ash:	.0003-.059%		1
	Texas, Colorado, North and South Dakota	Ash:	.01-1.0%		2
	South Dakota	Ash:	.12%		2
	West Virginia	Ash:	.013-.079%		2
	Pennsylvania, anthracite	Ash:	.01-.09%		2
	Australia	Ash:	.001-.06%		2
	Nova Scotia	Ash:	.0052-.065%		2
	Spitzbergen	Ash:	.001-.01%		2
	Germany, Neurode	Ash:	.11%		2
	Germany	Ash:	.3% max		2
	England, Newcastle	Ash:	.079%		2
	England, vitrain	Ash:	.05-.3%		2
	Russia	Ash:	.47-1.02%	3 out of 7 samples	2
	U. S.	Coal:	3-80 ppm	HTA, OE-DR, OE-P LTA, AA Whole coal, X-RF	4
	Northern Great Plains	Coal:	.7-40 ppm		1
	Eastern U. S., anthracite	Ash:	125-320 ppm	LTA	3
	Western U. S., high vol. bituminous	Ash:	45-610 ppm	LTA	3
	Interior U. S., low vol. bituminous	Ash:	61-350 ppm	LTA	3

Element	Type and/or Origin of Coal	Concentration In Coal or Ash		Remarks	Source
Ni (Cont'd)	Northern Great Plains, medium vol. bituminous	Ash:	20-440 ppm	LTA	3
	Great Plains, lignite and sub-bituminous	Ash:	20-420 ppm	LTA	3
	Illinois Basin	Coal:	8-68 ppm	HTA, OE-DR, OE-P LTA, AA Whole coal, X-RF	4
Se	U. S.	Coal:	.45-7.70 ppm	LTA, NAA	4
	Illinois Basin	Coal:	.45-7.70 ppm	LTA, NAA	4
Ag	Western U. S.	Ash:	.0001-.001%		2
	West Virginia	Ash:	<.0005-.0028%		2
	Germany	Ash:	.006%		2
	Eastern U. S., anthracite	Ash:	1 ppm	LTA	3
	Western U. S., high vol. bituminous	Ash:	1-3 ppm	LTA	3
	Interior U. S., low vol. bituminous	Ash:	1-1.4 ppm	LTA	3
	Northern Great Plains, medium vol. bituminous	Ash:	1 ppm	LTA	3
	Great Plains, lignite and sub-bituminous	Ash:	1-50 ppm	LTA	3
S	U. S.	Coal:	.42-6.47%	Whole coal, X-RF	4

Element	Type and/or Origin of Coal	Concentration In Coal or Ash		Remarks	Source
S (Cont'd)	Anthracite	Ash:	0.04-0.4%		3
	Bituminous	Ash:	0.04-12.8%		3
	Sub-bituminous	Ash:	0.12-6.4%		3
	Lignite	Ash:	3.32-12.8%		3
	Illinois Basin	Coal:	.85-5.59%	Whole coal, X-RF	4
Ti	England	Ash:	.41-1.55%	Cow peas ash .006% Oak wood ash .19%	2
	North Carolina, peat	Ash:	.20-.29%		2
	U. S.	Ash:	.3-1.5%		2
	West Virginia	Ash:	.60-1.38%		2
	Western U. S.	Ash:	.1-1.0%		2
	Northern Great Plains	Ash:	.15-2.6%		1
	Pennsylvania, anthracite	Ash:	.58-1.20%		2
	Northumber and Durham, England	Ash:	4.2-14.6%		2
		Coal:	.1-1.0% ash		
	Kent, England	Ash:	2.0-5.9%		2
		Coal:	.7-2.9% ash		
	England, vitrain	Ash:	.3-.8%		2
	North Staffordshire, North Wales	Ash:	3.2-17.7%		2
	England	Ash:	0-1.8%		2
	South Africa	Ash:	.46-1.18%		2
	U. S.	Coal:	.02-.15%	Whole coal, X-RF	4

Element	Type and/or Origin of Coal	Concentration In Coal or Ash		Remarks	Source
Ti (Cont'd)	Northern Great Plains	Coal:	95-2320 ppm		1
	Anthracite	Ash:	0.60-1.20%		3
	Bituminous	Ash:	0.30-2.4%		3
	Sub-bituminous	Ash:	0.36-1.2%		3
	Lignite	Ash:	0.0-.48%		3
	Illinois Basin	Coal:	.02-.15%	Whole coal, XR-F	4
U	Denver, Colorado	Coal:	.2-2%		2
	Rocky Mtn. area	Coal:	.005-.01%		2
	California	Coal:	.02% max		2
	Idaho, Bonneville Co.	Coal:	.02% avg		2
		Coal:	.13% max		2
	Idaho, Cassia Co.	Coal:	0.0-.1%		2
		Coal:	.097% max		
	Illinois	Coal:	<.001-.008%		2
	Indiana	Coal:	.001%		2
	Montana, lignite	Coal:	.001-.034%		2
		Coal:	.013% max		
	Nevada, Esmeralda Co.	Coal:	.003%		2
	Nevada, Churhill Co.	Coal:	.059%		2
	New Mexico, Sondoval Co.	Coal:	.001-.62%		2
	North Dakota, lignite	Coal:	.045% max		2
		Coal:	.14% max		
	Ohio	Coal:	.001%		2
	Pennsylvania	Coal:	.002-.014%		2
		Coal:	.019% max		

Element	Type and/or Origin of Coal	Concentration in Coal or Ash		Remarks	Source
U (Cont'd)	Pennsylvania, anthracite	Coal:	.001%		2
	South Dakota, lignite	Coal:	.08-.7%		2
		Coal:	.005-.02%		
		Coal:	.01%		
		Coal:	.005% avg		
	Utah, Southern	Coal:	.002%		2
	Northern West Virginia	Coal:	<.001-.003%		2
	Southern West Virginia, and Eastern Kentucky	Coal:	.001%		2
	Southern West Virginia, Southwestern Virginia	Coal:	<.001%		2
	Wyoming, sub-bituminous	Coal:	.001-.051%		2
		Coal:	.0022%		
		Coal:	.003-.016%		
		Coal:	.001-.014%		
		Coal:	.10% max		
		Coal:	.002-.007%		
	Austria, Trimelkam, lignite	Ash:	5.3-1500 gm/ton		2
	Austria, brown coal	Ash:	6-100 gm/ton		2
		Ash:	700 gm/ton		
	Belgium	Coal:	.0054-.009%		2
	Czechoslovakia	Coal:	.0002-.009%		2
	Hungary	Ash:	.017%		2
	Italy	Coal:	.000187-.000233%		2

Element	Type and/or Origin of Coal		Concentration in Coal or Ash	Remarks	Ref/Exp
U (Cont'd)	Japan	Coal	.00008-.0075%		2
		Coal	.00008-.0025%		
	Romania	Coal	.0017?-.0029%		2
	Sweden "Kolm", bituminous	Coal	1.4-2.4%		2
V	Mendoza, Argentina, lignite	Ash	21.41%	6.1% ash (38.22% V_2O_5)	2
	Argentina	Ash	21.6%	10.3% V_2O_5	2
	Yauli, Peru	Ash	21.3%	18% V_2O_5	2
	Australia	Ash	25.1%	1.7% ash	2
	Pennsylvania, Schuylkill Co., Buck Mtn. bed	Ash	11%		2
	Pennsylvania, Diamond bed	Ash	69%		2
	Peru, Yauli Province	Ash	12%		2
	Peru, Cahta Province	Ash	9%		2
	Russia, Urals, vitrain	Ash	31.4-9.2%		2
	Northern Great Plains	Ash	.001-.056%		1
	Texas, Colorado, North and South Dakota	Ash	.01-.1%		2
	West Virginia	Ash	.010-.019%		2
	Pennsylvania, anthracite	Ash	.01-.92%		2
	North Carolina, peat	Ash	.0006-.0017%		2
	Australia, Collie	Ash	trace-.17%		2
	England, vitrain	Ash	.04-.5%		2

Element	Type and/or Origin of Coal	Concentration in Coal or Ash		Remarks	Source
V (Cont'd)	England, vitrain	Ash:	1-7.9%		2
	England, Newcastle	Ash:	.05%		2
	Germany, Meurode	Ash:	.12%		2
	Germany	Ash:	1% max		2
	Nova Scotia	Ash:	.0061-.0244%		2
	Spitsbergen	Ash:	.01-.1%		2
	Japan, Fukui	Ash:	.007-.02%		2
	Japan, Beijo	Ash:	.062%		2
	Italy	Ash:	.14-.60%		2
	Russia	Ash:	.71-1.1%		2
	Russia	Ash:	.011-.034%		2
	Russia, Ural	Ash:	.10-2.85%		2
	Russia, Alai and Turkestan	Ash:	.006-.73%		2
	Northern Great Plains	Coal:	16 ppm		2
	U. S., Eastern Interior	Coal:	35 ppm		2
	Appalachian area	Coal:	21 ppm		2
	Australia	Coal:	110-670 ppm		2
	Nigeria	Coal:	100-200 ppm		2
	Japan	Coal:	3-109 ppm		2
	U. S.	Coal:	11-78 ppm	Whole coal, LTA, E-87 HTA, OE-DR, OE-F	4
	Northern Great Plains	Coal:	<1.4-59.0 ppm		1
	Eastern U. S., anthracite	Ash:	210-310 ppm	LTA	3
	Western U. S., high vol. bituminous	Ash:	60-860 ppm	LTA	3

Element	Type and/or Origin of Coal	Concentration in Coal or Ash		Remarks	Source
V (Cont'd)	Interior U. S., low vol. bituminous	Ash:	115-600 ppm	LTA	3
	Northern Great Plains, medium vol. bituminous	Ash:	170-860 ppm	LTA	3
	Great Plains, lignite and sub-bituminous	Ash:	20-250 ppm	LTA	3
	Illinois Basin	Coal:	16-78 ppm	Whole coal, LTA, S-RF HTA, OE-DR, OE-P	4
Zn	Kentucky, Crittendon Co,	Ash:	1.6%		2
	Kentucky, Hopkin Co.	Ash:	.16%		2
	West Virginia	Ash:	.0437 avg, .19% max		2
	Western U. S.	Ash:	<.01%		2
	Northern Great Plains	Ash:	.02-.7%	.02% detection limit	1
	Nova Scotia	Ash:	.0115-.055%		2
	England	Ash:	11.7%		2
	Germany	Ash:	2.1% max		2
	Yorkshire, England				
	Clarain	Ash:	.31%		2
	Durain	Ash:	.35%		
	England, vitrain	Ash:	.07%		2
	U. S.	Coal:	6-5359 ppm	LTA, AA	4
	Northern Great Plains	Coal:	<9-1000 ppm		1
	Eastern U. S., anthracite	Ash:	155-350 ppm	LTA	3
	Western U. S., high vol bituminous	Ash	50-1200 ppm	LTA	3

Element	Type and/or Origin of Coal	Concentration in Coal or Ash		Remarks	Source
Zn	Interior U. S., low vol bituminous	Ash	62-550 ppm	LTA	3
	Northern Great Plains, medium low bituminous	Ash	50-460 ppm	LTA	3
	Great Plains, lignite and sub-bituminous	Ash	50-320 ppm	LTA	3
	Illinois Basin	Coal	10-5350 ppm	LTA, AA	4

AA - atomic absorption
NAA - neutron activation analysis
OE-DR - optical emission, direct readout
OE-P - optical emission, photographic
LTA - low temperature ashing
HTA - high temperature ashing
X-RF - X-ray fluorescence

Source 1 Zubovic, P., T. Stadnichenko, and N. B. Sheffey, "Geochemistry of Minor Elements in Coals of the Northern Great Plains Coal Province", U.S.G.S., Bul. 1117-A, 1961, 58 pp.

Source 2 Abernethy, R. F. and F. H. Gibson, "Rare Elements in Coal", Bureau of Mines, Info. Circ. 8163, 1963, 69 pp.

Source 3 O'Gorman, J. V. and P. L. Walker, "Studies on Mineral Matter and Trace Elements in North American Coals", Office of Coal Research, Dept. of Interior, Contract No. 14-01-0001-390, 1971, 183 pp.

Source 4 Ruch, R. R., H. J. Gluskoter, and N. F. Shimp, "Occurrence and Distribution of Potentially Volatile Trace Elements in Coal", Environmental Protection Agency, EPA-650/2-74-054, 1974, 93 pp.